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AN INTRODUCTION TO ELECTRICITY

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BY

BRUNO KOLBE

PROFESSOR OF PHYSICS AT ST ANNE'S SCHOOL, ST PETERSBURG

Being a Translation of the Second Edition of 'Einführung in die Elektrizitatslehre,' with corrections and additions by the Author

TRANSLATED BY

JOSEPH SKELLON

LATE ASSISTANT MASTER AT BEAUMONT COLLEGE, OLD WINDSOR

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EDITOR'S PREFACE

THE many elementary books on electricity hitherto published in England all seem to labour under one of two defects. In the one class the student is expected to approach the subject with a mathematical equipment which requires some years of study, and which is acquired with difficulty by those who do not possess a mathematical turn of mind. In the other, the beginner is indeed taught experimentally; but the experiments, instead of being designed *ad hoc*, are for the most part the classical ones devised when our knowledge of the science was much less developed than it is now, and when the working hypotheses which give the best explanation of them had not yet seen the light. In the two cases the result is the same. The student starts on his journey with a very small number of electrical facts in his head, and most of these he has later to discard to make room for others acquired haphazard and in no definite order by himself. Of the many who yearly set to work with the idea of gaining a practical knowledge of electricity, all but a few ardent spirits forget their elementary experiments as fast as they can, and content themselves with the knowledge of the electric current that comes from the daily handling of it, while their use of the mathematical equipment acquired with so much labour, is confined to finding their way about the tables and other data given in technical

manuals. It is this state of things which has led to that contempt for electrostatics—itself the origin and foundation of all our knowledge of electrical phenomena—lately satirized by Sir Oliver Lodge,[1] and summarized by him in the phrase of the late Professor Fitzgerald, that this branch of the study of electricity is "one of the most beautiful and useless adaptations of nature."

From these defects it is conceived that the following pages are free. Originally delivered by Professor Kolbe in the form of lectures to his class in St Petersburg, he found himself unable to rely upon the knowledge of mathematical analysis possessed by his pupils; while, as nearly the whole of the apparatus employed had to be made by himself, he did not find himself compelled to adapt his experiments to the cumbrous and often antiquated instruments to be found in most laboratories. At the same time, he has fished in many waters, and has rescued many striking and luminous experiments from the back numbers of the scientific periodicals in which they lay buried from the gaze of the general public. As an instance, I may mention the experiment with wire-gauze on p. 22, adapted from Professor Vanderfliet, which at once gives the beginner a lively idea of the fact that electricity comports itself like a very mobile fluid; or that adapted from Sir Oliver Lodge, on p. 234, in which the student can actually *see* the current-carrying conductor wrapping itself round a permanent magnet. The equations to which the author has often found it convenient to reduce the results of such experiments are all, it is believed,

[1] *Electrons*, London, 1906, p. xiii.

within the understanding of anyone acquainted with the simplest rules of arithmetic.

The book, therefore, seems to me admirably adapted for the instruction of a class, but there is another point of view from which it may be regarded. If "the man in the street," or, in other words, a person of ordinary information and intelligence who has passed through the ordinary school curriculum, wishes to obtain some insight into the nature of electricity, there is hardly any English book at present to which he can be referred. Diagrammatic descriptions of machines for the commercial production of electrical energy will hardly help him to what he wants, nor will the analysis of complicated instruments, like Lord Kelvin's multicellular voltmeter. Here, on the other hand, he should find many simple experiments, which, even without actually performing them, should give him, when read, a fair apprehension of the laws they are intended to illustrate, and should enable him to appreciate the many popular lectures now delivered on the subject.

The translation which follows is made from the second German edition, published by Messrs Springer of Berlin in 1904–1905, and Professor Kolbe has kindly supplied many alterations and corrections in this, which extend not only to the text, but in some cases to the illustrations. It may therefore claim to be the latest expression of his views, and to be in that respect superior to other and earlier versions of his work. Progress in electrical science has been so rapid of late, that, in spite of this, some exceptions may be taken to certain passages in which he deals

with the speculative side of his subject; but in an elementary work there seemed no obligation to comment at length upon these. My task as editor has therefore been confined to seeing that the book appeared in readable English, and my few notes are distinguished from the author's own by the signature "Ed."

In conclusion, I may say that all the apparatus illustrated in the text is now manufactured for sale by the principal German firms who deal in these matters; but the student who may wish to import it is recommended, in order to avoid disappointment from breakages, to do so through some English firm. A still better and more economical plan would be to make it himself, which he should have no difficulty in doing with the help of the hints given in such books as M. Henri Abraham's *Recueil d'Expériences élémentaires de Physique.*

F. LEGGE.

ROYAL INSTITUTION OF GREAT BRITAIN,
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CHAPTER I

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Amber when rubbed attracts light bodies; but without addition or loss of weight.

I PUT before you a piece of amber. Amber, as you know, is fossil resin. I place it in one pan of a very delicate chemical balance, and into the other I pour sand until the beam of the balance is exactly level. Now I rub the amber on a piece of catskin. You see these tiny pieces of paper lying on the table are strongly attracted to it? What has taken place in the amber? I rub it again and then lay it once more in the scale pan.

Not the slightest change in its weight has occurred, consequently the amber has neither received nor lost any ponderable part of its substance. It has merely, without at the same time changing its qualities, assumed a new condition. We will put the amber aside, and after a short time we shall find that its power of attraction has become considerably weaker, and that it is soon lost altogether.

What is the nature of this transitory condition of the amber? Into this we must now inquire.

Historical.

The power possessed by amber, when rubbed, of attracting light substances was known 600 years B.C. to the ancient Greeks. They called amber "elektron." For more than two thousand years the experiments made with it were looked upon as mere trifles, fit only to amuse children. It was only in the year 1600 A.D. that the English physicist Gilbert, through experiments on the effects of friction on different bodies undertaken to test their powers of attraction, discovered that many substances, such as sulphur, glass, etc., possessed the same property as amber. To this property he gave the name "amber force," or electric force. Since then, the word electricity has been employed to indicate the *cause* of this property (*cf.* Appendix, 1). From other experiments he obtained some very striking, because contradictory, results, which at the time caused a stir. But it was not until the lapse of another century—that is, until the beginning of the eighteenth—that learned men gave full attention to electrical phenomena. Discoveries then began to follow in quick succession, and the number of experimenters and investigators increased to an extraordinary degree from decade to decade, until the dawn of the present century, when they culminated in many practical inventions of far-reaching importance, such as the electric light, electroplating, telegraphy, telephony, etc.; and such an impetus was given to the study of electricity that the present century may justly be called the electrical age.

Our present object is to make ourselves conversant

with electrical phenomena, and, at the same time, to follow, as far as possible, the historical development of the subject. If we obtain results which, on further investigation, we find to be untenable, we shall at any rate have accompanied in spirit the earlier students of the laws of nature, and be able to appreciate the difficulties which beset those who spared neither time nor trouble in their endeavour to overcome them.

After this digression, which will serve to indicate the aim and object of our researches, let us return to our first experiment. Instead of the amber, we will now make use of this more convenient and more efficient rod of English flint-glass, and as rubber we will employ leather treated with amalgam.[1]

Glass and amalgamated leather.

I rub the glass rod with the amalgamated side of the leather and bring it near to the pieces of paper before used. Even when it is at a distance from them of about 25 cm., the bits of paper are strongly attracted and again immediately repelled. I electrify the rod again, and bring it near the knuckle of my bent forefinger. Even at a distance of 4–5 cm. you can hear a crackling noise; and in the dark, minute electric sparks can be seen flashing across the intervening space. On this small board you will notice

[1] The amalgam usually employed in electric experiments consists of an alloy of two parts by weight of quicksilver heated with one part of tin and one of zinc. This hard and rough mass is pounded together in a stone or iron mortar and then smeared on a piece of leather, which has first been rubbed with tallow till it is quite soft. This amalgamated leather will be found most effective when the fat has been thoroughly absorbed, and the particles of amalgam not clinging to the leather have been got rid of by use.

some small pieces of the thinnest aluminium foil. I throw them into the air and bring the electrified glass rod near them. Nearly all these glittering morsels make for the rod, only to be as quickly repelled after contact with it. I follow them with the rod—they fly from it; and you see, with this magician's wand, as it were, I can drive them whither I will:—they flutter about like butterflies.

Now I rub this black ebonite[1] rod with this fox-brush.[2] The effect on the bits of paper, the finger, and the metal foil is the same as before, though weaker.

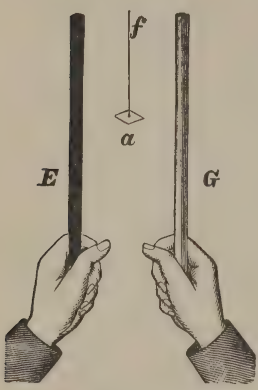


Fig. 1.—Electrical attraction and repulsion.

A thread hangs from a wooden bracket in the ceiling, to which a lozenge-shaped piece of aluminium foil has been attached. I again electrify both rods, and place them parallel to each other and equidistant from the aluminium foil (fig. 1). You again see both rods attract the foil, but only to repel it immediately; and the leaf repelled by the glass rod makes straight for the ebonite one, and *vice versa*, and hence the foil swings to and fro. Gradually the liveliness of the movement ceases, and after a time the action of the rods ceases too. How shall we explain these phenomena?

As the bits of paper and the aluminium leaves do not lend themselves easily to examination, I call in the aid of the *electric pendulum*. This consists of two

[1] Ebonite is caoutchouc vulcanized, *i.e.* combined with sulphur.
[2] Or a catskin.—*Ed.*

balls (about 3 cm. in diameter) made of the light pith of the stalk of the sunflower (*Helianthus annuus*[1]), which are fastened to the movable arms of the stand with silk fibre. Why silk, we will soon explain.

I bring the electrified glass rod near to the pendulum; the balls are attracted, and after contact so sharply repelled that they appear to swing over the rod as it is withdrawn, so that the threads are stretched out almost horizontally. I now remove the rod; the balls again fall back, but do not move, even when the arms of the stand are closed so that the hooks

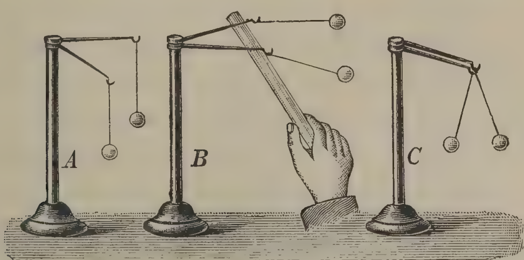


FIG. 2.—Electric pendulum of the usual construction, $\frac{1}{10}$ natural size.

on which the threads are hung are close together (C, fig. 2). Evidently between the two balls the same amount of active repulsion now exists as there was at the start between the rod and the balls electrified by it (B, fig. 2). In this state the electric pendulum is *charged.*

Now I touch one ball with my hand. My uncharged hand, by its mere movement towards the electrified pendulum, exercises upon it an appreciable influence, just as the electrified rod before did upon the

[1] Of single pieces stuck together (hollow) and finished off with sandpaper. One ball is coloured red. (In England the pith of the elder-tree is generally used.—*Ed.*)

then uncharged balls. Upon moving the hand nearer, the ball touches it, falls back, and is now attracted by the second and still electrified ball, and is then again repelled, but with distinctly less force than at first. I repeat the experiment, and the force of repulsion is further weakened—that is to say, the electric charge has decreased.

Let us repeat these experiments with the ebonite rod. The result is the same. From what we have observed we can formulate the following propositions:

(1) Uncharged bodies are attracted by charged bodies, and *vice versa*.

(2) By bringing charged bodies into contact with uncharged ones, the latter become electrified, and at the expense of the former.

(3) Two bodies, one of which has become charged by contact with the other, repel each other.

(4) Electrified bodies may be discharged (*i.e.*, become neutral) by contact with the hand.

With the exception of the peculiar behaviour of the piece of foil, which, you will remember, fluttered to and fro between the glass and the ebonite rods (fig. 1), we have reduced all the phenomena so far observed to distinct propositions. We must postpone the solution of the problem remaining, until we have examined the behaviour of other substances when submitted to the action of friction.

Capacity for electrification of various substances.

Here we have a number of rods and small metal plates of different materials. First I take a stick of resin or sealing-wax, and strike it with a fox-brush. The balls of the discharged pendulum are strongly (*i.e.*, at some distance) attracted. We notice the same thing happen when a piece of sulphur or a sheet of mica

is used. On the other hand, the attraction is weak, that is, is only perceptible in close proximity to the balls in the case of whalebone, seasoned wood, paper, bone, etc., and finally, it is quite unobservable in the metal rods, and in a piece of soap-stone or steatite. Glass rods behave very differently; some can be charged with ease, others not at all. Hence we can divide the bodies examined into those which may be electrified and those which may not; or, shortly, into *electric* and *non-electric* (Gilbert, 1600). Let us observe if this division can be kept to.

The electroscope is in most cases a much more convenient instrument than the electric pendulum (electroscope = electricity-finder). I now put before you two very simple, but at the same time very useful ones for our purposes.

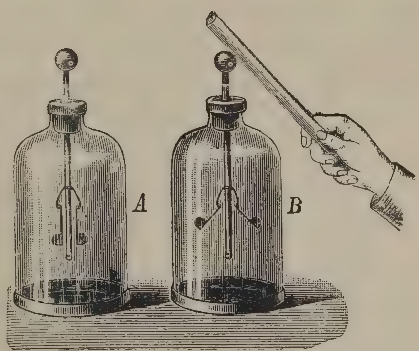


Fig. 3.—Paper electroscope, $\frac{1}{7}$ natural size.

This pattern has this advantage over those usually employed, that the position of the leaves can be better seen, and that they are not destroyed by strong charges of electricity.

Paper electroscope.

Here we have (fig. 3) two wide glass bottles, the bottoms of which have been cut off, and replaced by metal-plates with their edges turned up all round. The tops are closed by ebonite stoppers pierced by amber tubes, through which a nickel-plated brass rod has been pushed; to the upper end of this a rather large nickel-plated ball is screwed.

A hole is bored in the side of this so that a thick wire may be inserted. Inside the bottle two little curved pieces of fine, polished German silver wire are fastened to the conducting-rod, and to these are hung two strips of red tissue-paper, able to turn easily in the wire loop. At the lower end of each of these strips of paper is a crescent-shaped knob,[1] an addition which allows the position of the leaves to be seen from a greater distance.

Conductivity. I touch the ball of one of the electroscopes with the electrified glass rod. You notice that the leaves diverge (B, fig. 3), and still retain their position after the withdrawal of the glass rod. The electroscope is charged. If I now touch the ball on the conducting rod with the finger, the leaves fall together at once. Just the same thing occurs if I touch the electroscope with the end of a rod of metal, green wood, or steatite (soapstone) held in the hand. Now I touch the re-charged electroscope with a rod of whalebone—the leaves sink slowly. This also happens when it is touched with seasoned wood, paper, etc. If, on the other hand, I touch the electroscope with an uncharged rod of ebonite, no action takes place. This is also the case with a rod of sealing-wax, a strip of mica, a silk thread, etc.

To check this experiment, we will repeat it in a somewhat different manner. On the two hooks a_1 and a_2 (fig. 4) inserted into the holes in the balls, I lay

[1] The strip of paper is first cut into the shape of a *d*. The loop of the *d* is then folded back once upon its vertical stroke immediately before the attachment of the other end of the strip to the wire loop. On being released, it will stick out at right angles to the rest of the strip.—*Ed.*

a metal rod (m) and electrify one of the electroscopes (A) by touching it with the electrified rod. You will see that at the same moment both electroscopes become charged, and after the removal of the rod the leaves show an equal deflection or divergence. The connecting wire (m) may be of any kind of metal and of any length.

From two wooden brackets fixed to the ceiling, and parallel to the experiment table, hang some strong silk threads ending in small wire hooks. I take a fine wire about twelve metres long, fasten one end of it to the conducting rod of one of the electroscopes, and carry the wire along the insulated hooks across the whole length of the table and back again to the second electroscope, which is quite close to the first, so that you can see them both at once. I now charge one of the electroscopes, and you see how at the same moment the other diverges and shows the same strength of charge.

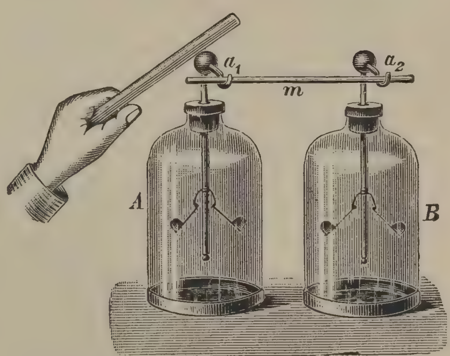


Fig. 4.—Demonstration of the conductivity of solid bodies.

Good conductors of electricity.

From these experiments we learn that the metal in an immeasurably short time has conducted the electricity from one electroscope to the other. Hence we call metals *good conductors* of electricity. To these good conductors steatite also belongs.

Now I replace the metal rod (in fig. 4) by a whale-

bone rod of equal length, and charge the electroscope A as before; the electroscope B becomes slowly charged, but does not reach so great a divergence as A. The same result follows if I employ, instead of the whalebone, a roll of paper or a piece of seasoned wood.

Bad conductors of electricity.

If I use longer rods of these materials, it takes longer before the electroscope B is charged, and the maximum divergence shown by it is smaller. Hence it follows that whalebone, dry wood, etc., are *bad conductors* of electricity (half-conductors).

Insulators.

Finally, if I connect both electroscopes by a rod of ebonite, sealing-wax, flint-glass, a strip of mica, or a silk thread, etc., the electroscope B receives no charge; therefore these materials are *non-conductors* or *insulators*[1] of electricity. Ordinary glass shows similar behaviour. Certain kinds insulate exceedingly well, among which are several kinds of green bottles; others conduct better than whalebone. We shall return to these later.

Connection between capacity for electrification and conductivity.

We now know that those bodies called by Gilbert *electric* are *insulators*. What about the *electrification* of the *conductors*?

Here you see a thick plate of steatite.[2] In one of its surfaces there is a shallow, conical hole into which an ebonite rod fits tightly. Holding the insulated handle, I flick the steatite with the fox-brush. Listen!—as the fingers are brought near to

[1] No perfect insulators are found, yet the conductivity of the substances named is so slight that we can only discover it by means of the most delicate methods. For the purpose of our experiments we can consider these bodies as true insulators.

[2] *Speckstein*, that is, soapstone. The German edition gives as an equivalent "talc," which in England is generally applied to mica.—*Ed.*

it, a crackling is heard and sparks are seen. I bring the steatite near the electric pendulum (fig. 2, p. 5)—the balls are strongly attracted. The good conductor steatite becomes strongly electrified by rubbing, if it is protected from contact with the hand by means of an insulating handle.

Let us repeat the experiment, using a metal plate into which is inserted an ebonite rod. When the fingers approach it, scarcely any crackling can be heard, but the balls of the electric pendulum are attracted and the electroscope is charged when touched by it. Insulated rods of whalebone and other partial conductors may also be charged, that is, *all properly insulated bodies may be electrified by rubbing or by contact with electrified bodies.*[1]

We thus see that the division of bodies into electric and non-electric is based on an error.

Behaviour of different kinds of glass.

On account of the important part which glass plays in electrical apparatus, I may be allowed here to spend a few moments on the remarkable behaviour of ordinary glass.

I touch with this glass rod, which has been lying on the table for some time, the charged electroscope—the leaves fall together rather quickly; that is, the glass conducts. Now I hold the rod for some moments in the flame of a spirit-lamp—it conducts no longer. Now I plunge the rod in pure water and allow the drops clinging to it to run off—it conducts better than before; wiping it with a dry cloth has not much effect, for an invisible film of water still remains on it. While lying exposed to the air, a

[1] Hence we understand the part played by the silk thread of the electric pendulum, and the ebonite stopper of the electroscope.

thin film of moisture was precipitated on it, which was turned into steam by the flame of the spirit-lamp. Evidently there is some connection between this (soda) glass and the moisture of the air. Ordinary glass is often hygroscopic.

Now I plunge the flint-glass rod into pure water and touch with it the charged electroscope. You see that the rod does not conduct, although drops of water still cling to it. If you examine the rod more closely you will find that the water does not form an unbroken film on it, but that it has gathered into many independent drops. Hence we see that moisture will not cling to flint-glass, so flint-glass is not hygroscopic. Hence its excellence as an insulating medium.

As, however, the high price of English flint-glass makes its universal employment for electrical apparatus impossible, the hygroscopic surface of ordinary glass must be covered with some substance which will make it proof against all attacks of atmospheric moisture. First the glass to be treated must be thoroughly dried and warmed, and then the part to be insulated is given a coating of shellac. More effective still is amber-varnish.

So far we have confined ourselves to the consideration of the *electrification* and *conductivity* of solid substances and the effect they have on one another. Now we will go a step further and compare the different kinds of electricity present in them.

Suspended from this electric pendulum (fig. 5) we see two pith balls, differently coloured. I charge the red ball (r) with the glass rod, and the green one (g) with the ebonite one. If I bring the glass rod near

both balls at the same time (fig. 5), the red ball, charged with the glass rod, is *repelled*, while the green one, charged with the ebonite rod, is *attracted*. In fig. 5, the original position of the balls is indicated by dotted lines.

If I bring the ebonite rod near, instead of the glass one, the contrary happens—the red one is attracted and the green one is repelled.

In both cases attraction takes place between the rod held in the hand and the ball charged by the other rod; on the other hand, as already observed, repulsion takes place between the rod and the ball charged by it. We must therefore conclude that in the glass rod and the ebonite rod, *two different kinds of electricity* have been called into being, between which there is an attraction, and thus the striking behaviour of the little metal leaf (in fig. 1) is explained.

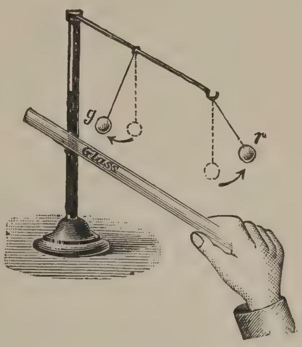


FIG. 5.

How many kinds of electricity, then, are there?

Only two kinds of electricity.

I discharge both balls of the pendulum, and then again charge one of them by means of a plate of steatite, held by an insulated handle, which has been rubbed by a fox-brush; the other I charge with a rod of resin or hard sealing-wax. The glass rod, when brought near, attracts both balls; the ebonite one repels both; *i.e.*, the electric conditions occasioned in the steatite and in the resin by rubbing are just the same as that of the ebonite. If, on the other hand, we charge the pendulum with a piece of mica or of rock crystal

also rubbed with a fox-brush, it acts as if electrified by the glass rod. No matter what substances we employ, we get the same result. There are two, and only two, kinds of electricity (Dufay, 1733). These two kinds are called *vitreous* electricity and *resinous* electricity, or, according to the proposal of Franklin (1747), *positive* electricity (+E) and *negative* electricity (−E). The law, then, is:—*Like electricities repel each other, unlike attract each other.*

Now you will ask: What about the stuff used to rub, or, as it is called, the rubber? This question is quite in order, and we will answer it at once.

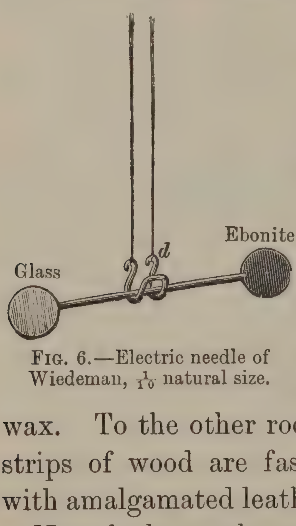


Fig. 6.—Electric needle of Wiedeman, $\frac{1}{10}$ natural size.

Particularly suitable for this purpose is the *electric needle* (fig. 6). Here we see two thin, very light tubes of ebonite. At the end of one a disk of glass is inserted in the notch shown; to the other end an ebonite plate of the same size is fastened by means of sealing-wax. To the other rod in the same manner two thin strips of wood are fastened, one of which is covered with amalgamated leather and the other with cat-skin.

Now look at the ceiling of the room: you will remark two wooden brackets into each of which a double hook has been screwed. From these, two silk threads hang down, supporting a wire loop or stirrup (*d*, fig. 6). I now rub the glass plate with the amalgamated leather, the ebonite plate on the cat-skin, and hang the rod with the two disks in the stirrup in such a way that the electric needle is horizontal.

If I bring the amalgamated leather near the electric needle, the ebonite plate is repelled and the glass one attracted; consequently, amalgamated leather is *negatively* electric (−E). Cat-skin, on the other hand, repels the glass plate and attracts the ebonite one, and is therefore *positively* electric (+E). Now I draw the amalgamated leather over some steatite. This becomes *negatively* and the amalgamated leather *positively* electrified, while when rubbed with glass this last shows −E. Hence we draw the following conclusions:

(1) The body rubbed and the rubber have opposite kinds of electricity.

(2) A body B, if rubbed with a body A, becomes *negatively* electrified, but may, when rubbed with a body C, become *positively* electrified.

For example, ebonite rubbed with fur, wool, etc., becomes *negatively* electrified, while if rubbed with amalgamated leather it becomes *positively* electrified. Even the nature of the surface exercises in some circumstances a certain influence. Rough surfaces are more likely to become *negatively* electrified than smooth ones. Polished glass rubbed with flannel acquires +E, dull glass −E; smooth polished ebonite surfaces when rubbed with certain kinds of leather or with albumenized paper show +E, while rough surfaces show −E.

If we rub a number of bodies together, and then so arrange them that at the one end of the series is placed that which, when rubbed with any of those which come after, always shows +E, while the series ends with that which, when rubbed with any of the foregoing, only shows −E, then we can so

insert the remaining bodies that each one, when rubbed with the one immediately preceding it, yields *negative*, and with that following it *positive* electricity. In this manner we get the so-called electrostatic tension[1] series.[2]

ELECTROMOTIVE SERIES.

+	Flint glass	Cat-skin	Mica	Common glass	Flannel	Ground glass	Silk	Cotton	Linen	. . .	Metals	Cork	Resin	Ebonite	Amalgamated leather	Steatite –

As a rule, two bodies when rubbed together become the more strongly electrified the further they are from each other in the series—hence the bodies at the far ends receive the strongest charges of all; yet, other circumstances being equal, a pliant rubber is more effective when the thing rubbed is stiff. Hence the best rubber for glass is amalgamated leather; and for steatite or ebonite, fur.

We will now examine the effect which the two kinds of electricities have upon each other.

I charge one electroscope (A), by means of the electrified glass rod, with $+E$; the other one (B), by means of the electrified ebonite rod, with $-E$. If I bring the glass rod down from above at the same time towards the two electroscopes, you see (fig. 7) that the leaves of the electroscope charged with similar

[1] In England sometimes called electromotive series.—*Ed.*

[2] By mistake our flint-glass rod was once used to stir up a solution of alkali. Since then, when rubbed with fur, it becomes *negatively* electrified. Only a small part near the wooden handle has kept its original character. Probably the formerly very smooth surface has become slightly corroded.

(+E) electricity by means of the glass rod divide still further; those of the electroscope B charged with unlike (−E) fall together. In fig. 7 the original position of the leaves is indicated by dotted lines.

The same thing takes place if we use the electrified ebonite rod instead of the glass one; only the electroscopes exchange parts.

Test by electroscope.

In this manner we have discovered a convenient method of determining the kind of electricity of any body. We need only to slowly[1] bring the body to be examined near an electroscope charged with a known kind of electricity: if the gradual approach of the body to be examined causes an enlargement of the distance between the leaves, then the body has the same kind of electricity as the electroscope; and, on the other hand, the opposite kind if the leaves fall together.[2]

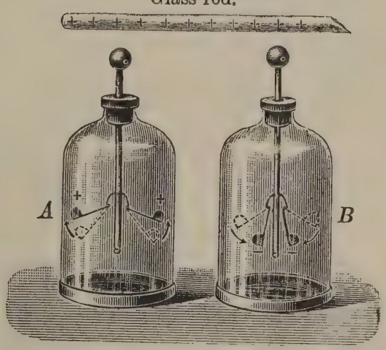


Fig. 7.—Glass rod. Detection of + and − electricity by electroscope.

It may often be desirable to find out what kind

[1] The *slow* approach of the testing-rod is important, because when using a body too strongly electrified the earlier falling together of the leaves might not be remarked, and the further divergence of the leaves following on another approach might be wrongly interpreted.

[2] The divergence of the leaves forms (when carefully carried out) a more reliable criterion than their sinking, because the mere approach of an uncharged conductor, *e.g.*, the hand, may cause a slight falling together of the leaves. The cause of this will be clear to us later, when we study the phenomena of influence.

of electricity a charged body contains. In such case it is only necessary to bring slowly near it a body which contains a charge of known sign. The rule remains the same. I charge both electroscopes with $+E$, so that the divergence is the same, and connect the two balls with a fine wire, which has an insulated handle in the middle.[1] You see no effect. The same thing happens if both pieces of apparatus are equally charged with $-E$. If two similar electroscopes are charged with equal amounts of the same kind of electricity, no electricity passes from one body to the other.

$\pm E = 0$. I now charge the electroscope A with $+E$ and the other with $-E$, so that the divergence of the leaves is exactly the same in each.

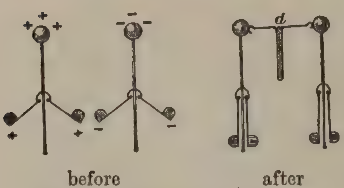


Fig. 8.—Conductive connection.

As both pieces of apparatus are constructed in exactly the same way, we must take it that both electroscopes hold equal quantities of electricity. I again take the insulated wire (*d*, fig. 8) and touch with it the balls of each, by which means communication is established between the two bodies charged with opposite electricities. You see that in both electroscopes the leaves have fallen entirely together, *i.e.*, the instruments have been discharged. We learn, therefore, that like quantities of positive and negative electricities neutralize each other; or, shortly, that

$$\left.\begin{matrix}+E\\-E\end{matrix}\right\} = 0.$$

[1] A simpler plan is to use a wire with a thick rubber coating, only the ends being left bare.—*Ed.*

CHAPTER II

Distribution of electricity on an insulated conductor. How the full charge of a proof-ball can be transferred to the electroscope. Graduation of the electroscope. Analogy between the electroscope and the thermoscope. Aluminium electrometer. Graduation scale. Experiments with conical conductor. Variations of electric density on unequal surfaces. Constancy of the degree of electrification of an insulated conductor. Distribution of electric density on an insulated conductor in relation to the surface curvature. Action of points. Discharging power of a flame.

The first day's journey has come to an end. A traveller, who wishes to fix in his mind the road which he has traversed, will do well, from time to time, to cast a glance behind him so as to note the windings of his path, and to impress upon his memory any particularly characteristic spots. Thus, as we wander through the still greatly unexplored domain of electricity, we will cast from time to time a glance behind, and pass in review before our mind's eye the most important phenomena observed.

We have just learned that: Retrospect.

(1) All bodies when rubbed or touched by "electric" (*i.e.*, electrified) bodies themselves become electric; but those which conduct must first be insulated, so that they may retain the electricity that they have received. The nature of the rubber has a very important bearing upon the strength of the electricity

produced by rubbing. The further apart rubber and rubbed are in the electrostatic tension series, the greater as a rule is this strength.

(2) If an electric conductor is connected to the earth, which is itself a conductor—as, for instance, by being touched by the hands—it will be discharged, *i.e.*, it will be made unelectric. If, on the other hand, the connecting wire be insulated, a part of the electric charge passes from the electrified body along the non-electric conductor, which itself becomes electric or charged by communication; if two bodies are charged with equal amounts of electricity, no electricity passes from one body to the other when they are brought into contact.

(3) There are only two distinct electrical states, and these are opposed to each other; for when a body is charged with equal quantities of $+E$ and $-E$, they neutralize each other. The rubber and the thing rubbed have always opposite kinds of electricity. By friction, polished English flint-glass acquires *positive* electricity, and resin (or, better, soapstone) *negative* electricity. When an electrified body is slowly brought near a charged electroscope, and a further divergence of the leaves is caused, the body possesses the same kind of electricity as the electroscope; but the opposite kind, if the leaves fall together. Like kinds of electricity are repelled—unlike are attracted.

We will now ask ourselves the question, Where is the position or seat of electricity in an electrified body? Since, as we know, insulators do not conduct electricity, it is probable that the electricity will in their case remain where it was produced by friction or communicated by contact, *i.e.*, at the spot touched.

If this supposition is right, the discharge of an electrified insulator can only happen when this spot is touched by the hand. We can soon convince ourselves of this by an experiment.

I charge an electroscope with an electrified flint-glass rod. At the approach of the rod the leaves diverge further, and indicate thereby that the rod is electrified. Then I cover the electrified surface of the rod with my hand, and you will see the part not in the immediate neighbourhood shows itself as still strongly electrified. Now I try, by grasping it in successive places, to discharge it, but I cannot quite succeed in doing so. To discharge it completely I must pass it through the flame of a spirit lamp,[1] or wave it backwards and forwards above it. This discharging power of the flame we will examine more carefully later on.

Where, then, is the seat of the electricity in, of course, an insulated conductor?

Here we see (A, fig. 9) a piece of fine-meshed pliant wire gauze, which is insulated by means of the ebonite stand (i). On both sides of this gauze movable strips of paper are fastened, those on one side being red, and on the other green. By means of the insulating handles (g_1 and g_2) I can bend the gauze as I like. Now I charge the gauze with the flint-glass rod by laying it on the upper edge of the net,

[1] Every flame free from soot will serve to discharge an insulator (*cf.* end of this chapter). As soot conducts electricity, a deposit of the same on bodies to be used as insulators must be carefully avoided; and the more so, because only the most thorough washing can remove it from surfaces that are at all rough. This washing should always be done when an insulator is to be entirely discharged. *Cf.* note 1, p. 83.

and then draw it along so that as much of the surface of the rod as possible may come into contact with this edge. You see how all the strips of paper are raised up, and, now that the gauze is straight, show equal divergence on both sides of it (B, fig. 9).

Seat of electricity in insulated conductor.

Now I ask you to fix your attention on the little red strips on your side of it. I grasp both insulated handles (g_1 and g_2) and bend the net—turning the hollow side towards you—gradually into the form of a hollow cylinder. You notice how the

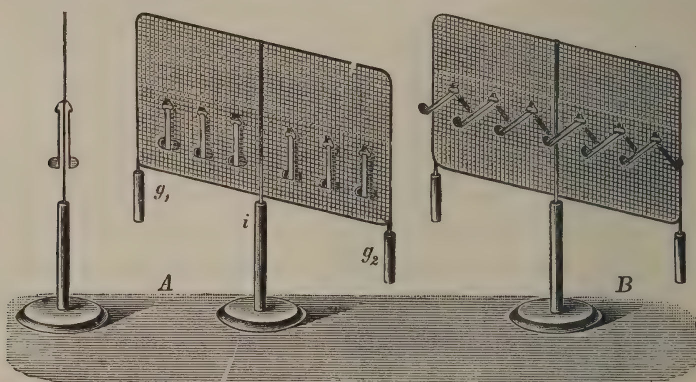


FIG. 9.—Vanderfliet's insulated wire gauze, with movable strips of paper, slightly modified, $\frac{1}{10}$ natural size.

little red leaves inside the hollow thus formed gradually sink, and—even before both edges of the gauze touch each other—fall entirely down (A, fig. 10), while the little green leaves outside show a considerably greater divergence than before. Now I bend the cylinder slowly back again: the red leaves gradually again raise themselves, while the green ones sink. When the gauze regains its flat condition the divergence of the red and green leaves is again the same (B, fig. 9). I bend the gauze more, so that the red leaves are on the convex side. You notice

that they raise themselves still higher, while the green ones sink finally against the gauze. We gather from this, that when the gauze is held quite straight the electric charge is equally distributed on both sides of it; but as soon as it is bent the charge flows from the concave side to the convex or outer surface.

Thus, *the seat of the electric charge of an insulated conductor is its outer surface, and in the inside of an*

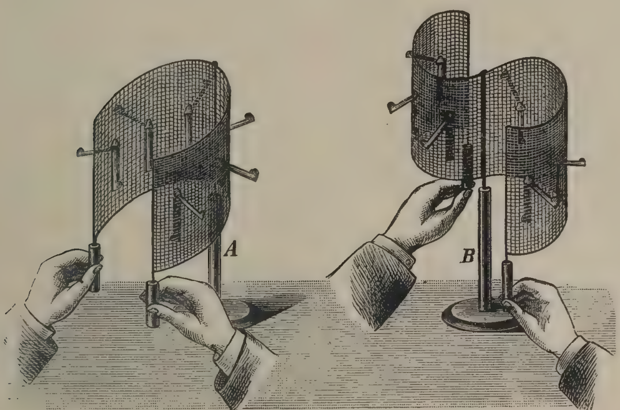


FIG. 10.—Demonstration of distribution of electricity.

almost closed hollow conductor there is evidently no electricity. This is a most important law.

When each side of the gauze is partly concave and partly convex, the electric charge must appear on both sides of it, but only on the convex parts. I give the net this form—and you see that this is actually the case (B, fig. 10). The middle of the gauze, where one curve merges into the other, forms the boundary of the electrification. This boundary is called the point of flexion.

Let us suppose that the electric charge of a body consists of very minute particles of electricity—this Lenz's explanation.

must be taken as a mere figure—then we have a simple explanation of the phenomena observed on the basis of the repulsive force of like electric particles. This is not very scientific, but for the moment it will suffice.[1]

Let us next suppose that all electric particles on the inner side of a solid ball are equally distributed, and let us fix our eyes on any one particular particle e (fig. 11), whose distance from the surface $= a$. What will happen then? Presumably the particle e will be repelled by all the neighbouring particles of the same kind of electricity. Inside the circle described with a radius of $\frac{1}{2}a$ are always found two particles at the same distance from the centre but opposite—*e.g.*, p and q, or x and y, etc.; that is to say, the force of all electric particles lying about e in the circle must, with regard to e, *cease entirely*. There now remains the repulsive force of all particles which lie outside the circle.[2]

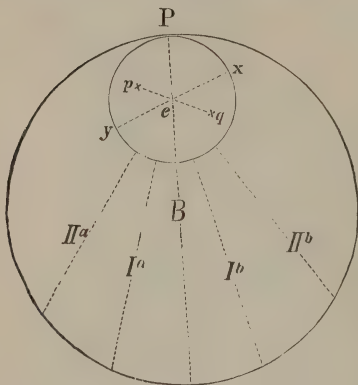


FIG. 11.

How easily, as it appears, will all particles lying in the line B exercise upon e a repulsive force in the direction BP!

Every two symmetrically placed rows, as I^a and I^b,

[1] On the electronic hypothesis, this is no mere figure, but strictly true.—*Ed.*

[2] Strictly speaking, we must consider both circles to be spheres. The drawing, fig. 11, therefore represents a cross section. The ratios between the electric particles, obtained for both circles, also apply to these spheres.

or II^a and II^b, will, by their combined action, according to the law of the parallelogram of forces, yield a resultant force which will exert a repulsive force on e in the direction BP also. Therefore the particle of electricity under pressure of all repulsive forces has to move as far as it can go, *i.e.*, *to the surface of the conductor* B. Since what has been said applies equally to every other particle of electricity, it follows that all particles of electricity must make their way from the inside to the surface of the conductor (Lenz).

From the laws we have found governing the distribution of electricity in an insulated conductor, some important results follow, thus :

(1) A hollow metal ball can, when brought into contact with a known amount of electricity, absorb just as much electricity as a solid ball of the same dimensions.

(2) An electrified conductor, introduced into the interior of a hollow metal body, must, when it comes into contact with the inner surface, yield up its entire charge to the enclosing metal.

Thanks to the first of these results we can use for the accumulation of electricity a *hollow* conductor—which will thus be as light in weight as possible—without diminishing the force of the charge. The second result we shall shortly turn to a very particular account, but I will first show you what influence the enlargement of the surface of an electrified conductor has upon electric density.

A metal tube (m) provided with two movable strips of paper is inserted into an ebonite tube (R, fig. 12); this is connected with an indiarubber bellows like that of a spraying-bottle. If I now plunge the expanded mouth of the metal tube into a

solution of soap and electrify it so strongly, after removing it, that the leaves stand out almost horizontally, then, when I blow air through the tube, a soap-bubble will form, and you can see that the greater the soap-bubble, the less is the divergence of the leaves. If I carefully place a rubber tube on the ebonite one (R), I can, by exhaustion, reduce the size of the soap-bubble. You see how the leaves again raise themselves, at first slowly, then more and more quickly.

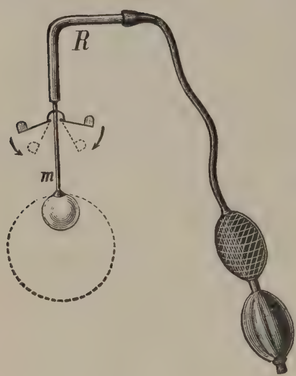


FIG. 12.

Dependence of electric density on conducting surface.

As the same quantity of electricity must be distributed, as the bubble grows, over a greater surface, there comes on any particular portion of the surface (as, for example, 1 sq. cm.) less electricity than before; the electricity must have become less dense. From this it follows: *the charge remaining the same, the electric density of a body decreases in the same ratio as the surface increases.*[1]

And now comes the interesting question: How is the electricity distributed on an insulated conductor which is not spherical, but which shows different contours in different places? Before we can answer this question, we must look about for some suitable measuring instrument.

[1] This experiment is also an argument for the discontinuous nature of electricity, in the same way that the expansion and contraction of a metal under alternate changes of temperature go to prove the discontinuous nature of matter.—*Ed.*

In the fact that electricity always displays an affinity for the outward surface of a conductor, we have a first-rate means of transmitting the entire charge of a small conductor to an electroscope—as, for instance, that of a small metal ball fastened to a rather long ebonite rod, by bringing this "proof-ball," as it is called,[1] into contact with the inside of a hollow metal sphere, screwed on to an electroscope.

Analogy of electroscope and thermoscope.

Next, if we are able to discover a source of electricity of the greatest strength possible, we shall be in a position to observe the angle of divergence caused by one, two, or three equal charges of the proof-ball; and if the electroscope is provided with a scale, we can read this off, or, which is more convenient, we can make a new scale, marking the positions of the leaves at the first, second, and third charges. In this way, by means of the particular position of the leaves at any moment, we can estimate, in units of electricity—for the present quite arbitrary ones—the degree of charge or electrification in units of electricity. Hence the electroscope will be to us for the measurement of electricity, what, before the discovery of the fixed point of temperature (freezing and boiling points of water), the thermoscope was to physicists for the measurement of heat before the time of Réaumur and Fahrenheit.

Just as this thermoscope, graduated in inches or millimetres, will serve us well for the comparison of differences of temperature, so this calibrated electro-

[1] In most English text-books, the use of a "proof-plane," or metal disk fastened to an insulating handle, is recommended. A great part of the charge escapes from the sharp edge of the disk, and the sphere is therefore preferable.—*Ed.*

scope will put us in a position to compare the differences of degree of electrification with each other. For the present we do not require more.

As the paper electroscope is not delicate enough to indicate small degrees of electrification, we will use the aluminium electrometer (fig. 13), constructed in the main in the same way, except that, instead of the two little paper leaves, a single small leaf of aluminium

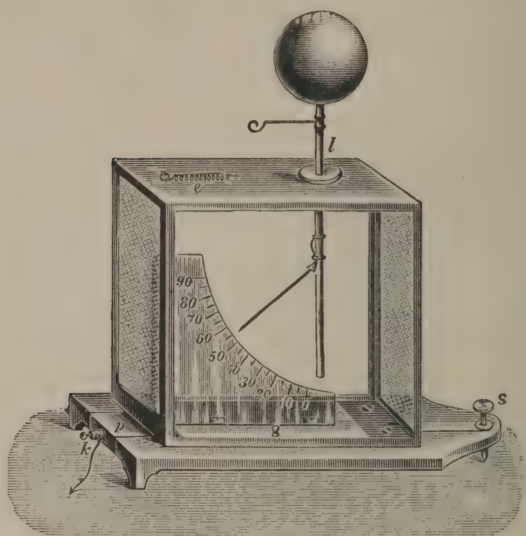


Fig. 13.—Aluminium electrometer with graduated scale, ½ natural size.

foil is employed, by which means the sensibility of the apparatus is increased by fifty per cent. In the plane of oscillation a graduated scale engraved on mica is fitted. The case is of tin-plate with one side of silvered glass, the ends being further covered inside with wire netting.[1]

[1] This description is not very clear. All four sides of the tin-plate frame are fitted with slides of clear glass, the two smaller panes being covered with wire gauze in addition. The pane behind

From a distance you will scarcely be able to see distinctly the fine aluminium leaf, so we will darken the room,[1] and by means of a powerful lamp and projection lens throw upon a white screen a much enlarged picture of the little leaf and the scale. From your places you can see the position of the little leaf. Fig. 16, p. 32, shows you the arrangement of the experiment in the most simple form (*cf.* Appendix, 6). On the screen the graduated scale is shown.

Since the projection lamp and the gleam of the illuminated screen lights up the room sufficiently to see all objects distinctly, you will be able to follow easily all my manipulations in the following experiments.

As our source of electricity we will take this conductor (fig. 14), which is insulated by its ebonite stand. The conductor consists of a tin cylinder (*ec*) to which a tin cone (*ac*) has been soldered. A hollow cone is inserted into the other end. The entire surface of the conductor is silvered and polished.

Now I charge the conductor by means of a flint-glass rod. Listen carefully, please. If I try to put a stronger charge into the conductor, you hear at the

the leaves is so arranged that a mirror can be substituted for it. Instead of the ordinary knob, a hollow nickel-plated ball not less than 5 cm. in diameter, with an opening at the top, is screwed on the top of the conducting rod.—*Ed.*

[1] With a strong light, such as that of an electric incandescent lamp of from 25–50 candle-power, half of which is silvered over, it is only necessary to darken the window nearest the experiment table, and so to place the screen that the light from other windows will not strike directly upon it.

end (a) a soft hissing. Evidently the surplus electricity flows out from the tip.

Now, with the nickel-plated and polished proof-ball fastened to a long ebonite rod, I touch the middle of the outside of the cylinder (d, fig. 14) and lower the proof-ball into the hollow ball of the electrometer, until it touches the inner surface. You see the leaf marks a divergence of 23·3°. I discharge the electrometer and repeat the experiment, putting the proof-ball always upon the same spot of the conductor; we get divergences of 23·5°, 23·4°, 23·2°, 23·3°, 23·4°: *i.e.*, the divergences of the electrometer are almost the same. Hence we may gather that our conductor —which we charge from time to time until it hisses —furnishes a constant source of electricity, which we can for the present use as a gauge for the electrometer.

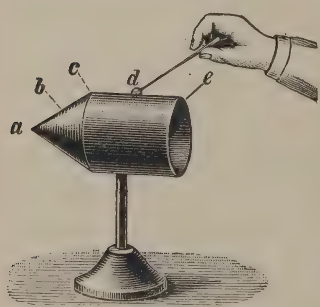


FIG. 14.—Conical conductor, $\frac{1}{10}$ natural size.

Graduation of the electrometer.

If we mark in blue pencil on the white screen the turning point of the little leaf and its position at the first, second, third, etc., charge by the proof-ball, there arises before our eyes a graduated scale. If we now note the position of the leaf according to the graduated scale, later on we may at our leisure engrave the scale of degrees on a piece of mica,[1] and place

[1] A sheet of mica does not break so easily as glass, and can easily be cut with a pair of scissors. Before painting the scale it is recommended to cover the completed piece of mica with collodion. The scale itself is first drawn on white cardboard and

it in the electrometer case in lieu of the graduated scale hitherto used. Of course, we must write the proper numbers the reverse way, so that they may appear right on the white screen.

In this way, then, the removable projection scale

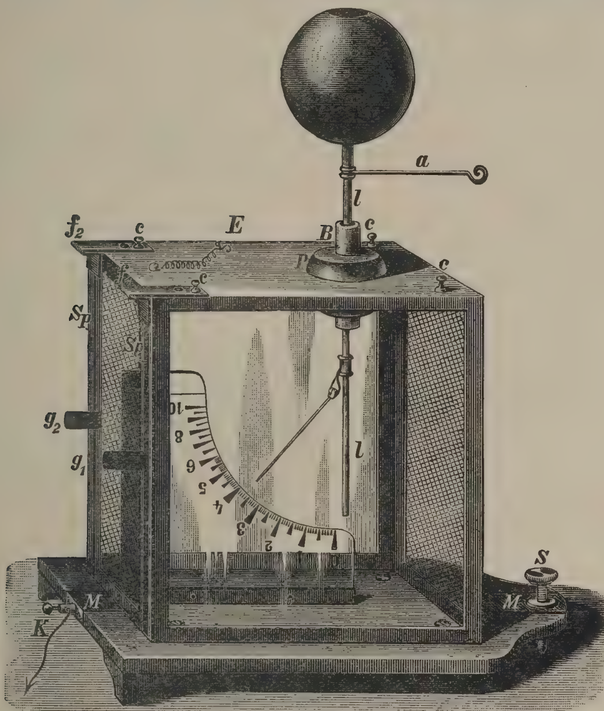


Fig. 15.—Aluminium electrometer with graduated scale for projection, $\frac{1}{3}$ natural size.

of the electrometer has originated which I show in fig. 15. If a more constant supply of electricity and a more exact, that is a larger, graduation is substituted for this, it will make no practical difference.

then pricked through (marks and figs. 0, 3, 6, 9, should be in red, others in blue or black). Transparent colours are the best, such as carmine and indigo.

This electrometer (fig. 15) has a few advantages over the first one (fig. 13). In the ebonite stopper (P) an amber tube (B) is inserted, through which the conducting rod (*b*) is pushed.

By this improvement, discovered by Professor Weinhold of Chemnitz, the insulating power of the instrument is made greater and more lasting.

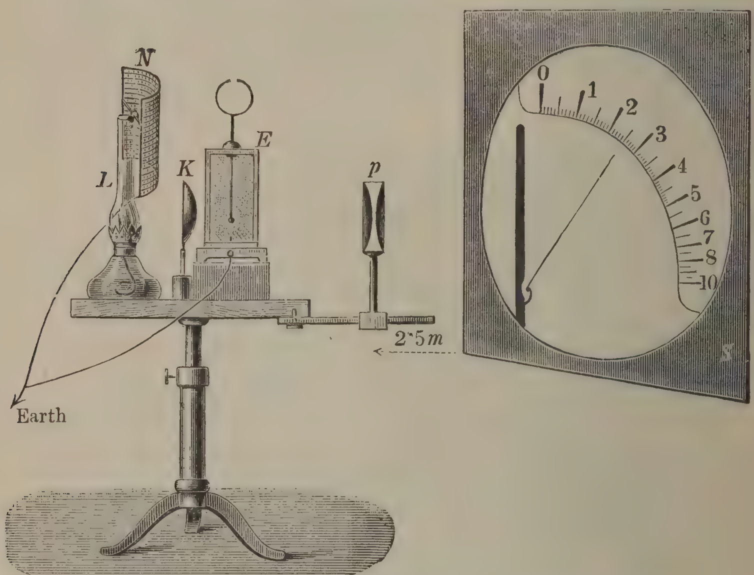


FIG. 16.—Projection of the electrometer scale ; apparatus $\frac{1}{10}$ natural size, scale $\frac{1}{20}$.

In order that you may all clearly see the divergence of the leaves, I will place the electrometer on the projection table (fig. 16), and on the white screen you will see the scale and the shadow of the leaves much enlarged. We shall always use this projected scale when working with the electrometer. The framework of the case of the electrometer will also be connected to earth, by taking a wire from the binding screw

to the water-pipes. In fig. 16 this is indicated by the arrow (*cf.* fig. 32).

The escape of electricity (see p. 30) from the end of the conductor, observed by us when the charge is too powerful, brings before us the question:—How does the electricity distribute itself on the surface of an insulated conductor—*i.e.*, is it distributed uniformly or not?

We will arrange for ourselves a very simple experimental electroscope. In the hole drilled into the side of the small proof-ball we will fix a strong German-silver wire, supporting at its middle two wire loops, to which two strips of paper are lightly attached (A, fig. 17). If I place the proof-ball provided with this little electroscope on the freshly charged conductor, the leaves separate.

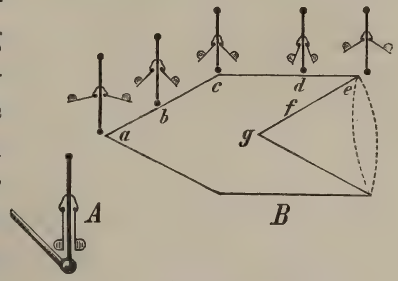


FIG. 17.

If I now move the electroscope to and fro over the entire outside surface of the conductor, you see the divergence of the leaves varies from time to time.[1]

We perceive at once that the divergence of the leaves is greatest at the point a, and next strongest at the circular corner (e), at the extremity of the cylinder; it begins to grow weaker at the still circular but more obtuse angle c, and it is weakest in the middle of the cover of the cylinder (d).

[1] The experiment will be more successful if the auxiliary electroscope is placed on the indicated point of the conductor and then moved a little distance from it. Still, the next experiment (p. 35) is really the only decisive one.

Distribution of electric density.

Suppose we imagine we cut sections of the hollow conductor (fig. 17) perpendicular to the long axis—*e.g.*, through the points *a b c d e f*. We thus get transverse sections, which increase constantly from *a* to the angle *c*, but remain the same size from *c* to *e*. The greater is the circle, the less pronounced is the curvature of the circumference; therefore, the curvature of the sectional circles becomes less from *a* to *c* and remains unchanged from *c* to *e*. On the other hand, the curvature of the surface of the conductor in the direction perpendicular to the plane of section (therefore in the plane of the paper, fig. 16) at the points *c*, *d*, and *e* is different, for the edge *c* forms an obtuse angle, and the corner *e* an acute angle; while at *d* it becomes a very obtuse angle—that is, a straight line. Keeping in view that in determining the curvature of a surface we must take into consideration the curvatures at the various turns, we come to the conclusion that the total curvature is greatest at the point *a*, next greatest at the edge *e*, then at *c*, *b*, and least at *d* in the middle of the cylinder.

This gives one the impression that the electricity accumulates in greater force, or, so to speak, is intensified at the more curved outer surfaces. If we call this apparently denser distribution of electricity electric density (*cf.* p. 26), then we may state that:

The *electric density varies on all parts of the surface of a charged insulated conductor with the curvature, or generally the greater the curvature the greater the density.*[1]

[1] Strictly, this only applies to insulated balls connected by long thin wires (*cf.* fig. 21).

This appears, not immediately, but yet more plainly, when by means of a proof-ball we transmit a charge from the given points a b c d e f g to the electrometer (see p. 30). We get:

At the Points on the Surface.		a	b	c	d	e	f	g
(a) When the charge of the conductor is the strongest possible	in electric units .	6·0	1·1	1·4	0·8	3·2	0·5	0
	Ratio . .	7·5	1·4	1·75	1·0	4·0	0·63	0
(b) When the charge of the conductor[1] is weak	in electric units .	2·3	0·45	0·52	0·3	1·2	0·2	0
	Ratio . .	7·6	1·5	1·73	1·0	4·0	0·66	0

We see in this case, also, that on the outside surface the electric density is greatest at the point a, next at the circular-shaped edge e, and so on, and least at the middle of the surface of the cylinder (d). On the inner surface of the hollow cone, the electric density, beginning at the edge, diminishes very rapidly, and at the deepest point (g) it is zero. The second series of experiments with the weaker charge indicates that the relation of the electric densities at the points concerned remains constant, and therefore does not depend upon the strength of the charge.

The numerical values we have found for the electric densities have put us in a position to draw a graphic

[1] In this case I plunge the electrified proof-ball carefully into the hollow ball of the electrometer, *without touching it*, and then touch the conical conductor with the proof-ball (without discharging it) on the other particular spots. The admissibility of this proceeding follows from the experiment (A, fig. 20) already described.

representation of the variation of the electric density on the conductor and—for comparison—upon an insulated hollow ball. On the sectional drawing of the conductor (A, fig. 18) and the ball (B) we draw lines to the respective points (*a b . . . g*) in the direction of the electric repulsion.

These lines are proportional to the measured densities of the electricity at these points. If we now connect the end points of these lines, we obtain from the conductor the curved line resembling it—*a b c d e f g* (A, fig. 18).

Let us imagine this curve to rotate round the axis

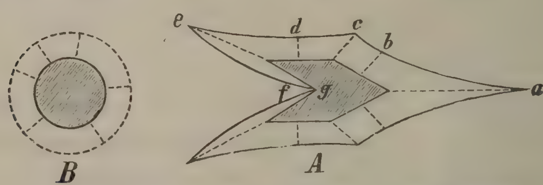


FIG. 18.—Graphic representation of the electric density.

(*a . . . g*) of the conductor: it describes a surface of revolution which is called the level [equipotential] surface of electrical density.

In the case of the ball (B, fig. 18), the electric density is equal over the whole surface, and the level surface of the electric density is also a spherical surface.

I now connect the conducting wire of a paper electroscope, to which I have screwed[1] a small ball,

[1] It must be expressly stated here that all electrical apparatus employed in these experiments must be fitted with screws of the same thread, so that all balls, plates, etc., may be interchangeable at will. By this means the experiments will be much simplified, and the number of pieces of subsidiary apparatus much lessened.

by a very fine bare copper wire with the insulated proof-ball.[1]

If I now charge the conductor and touch it at some spot with the proof-ball, the electroscope indicates a certain divergence, which does not change if I draw the proof-ball over the whole length of the surface of the conductor, or when I touch the point of the conductor or the inmost point of the hollow cone (fig. 19).

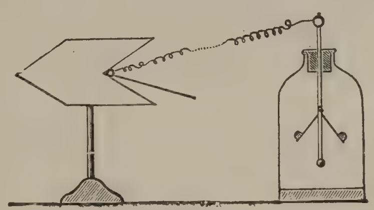


FIG. 19.

Similarly, we may connect the electroscope with the bent electrified gauze (fig. 10, p. 23)—still the divergence of the electroscope remains the same, whether the wire touches the concave or the convex side of the gauze.

Constancy of degree of electrification in insulated conductor.

To our astonishment, therefore, we observe that the effect which an electrified conductor exercises upon an electroscope set up at some distance and joined to it by a fine wire, remains the same, whether the connecting wire is brought into contact with any point either of the conductor's outer surface or its inner wall. This peculiar condition of an electric conductor which we notice in an electroscope connected to a conducting wire we call the electroscopic state of a body. The different degrees of

[1] It is advisable to fasten the wire by a knot in the middle of the rod, so that it may stretch tightly from the ball to the rod. In this way contact between the wire and the conductor will be avoided. (In the figure this cannot be well shown.) Still more instructive is the employment of the paper electrometer instead of the electroscope, of course with projection of the scale.

the electroscopic state may be called "degrees of electrification." We can put it shorter thus:

The degree of electrification of a conductor has upon its entire surface—both outer and inner—the same value. Thus the degree of electrification essentially differs from the electrical density, which, as we saw, may have very different values at different points of the same conductor.

Later on we shall have to go more thoroughly

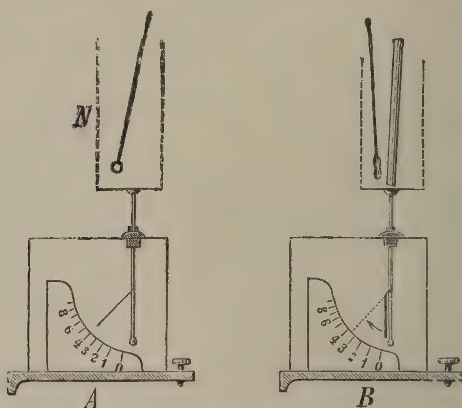


FIG. 20.—Faraday's experiment, $\frac{1}{10}$ natural size.

into the degree of electrification of bodies. For the present we will only examine the influence of an electrified body upon an unelectrified conductor surrounding it almost completely.

Faraday's law.

I screw upon the electrometer a cylinder of wire gauze open at the top, having a metal bottom, and provided with a female screw (N, fig. 20, A). If I now place the electrified larger proof-ball in the hollow of the wire-gauze cylinder without touching the gauze, the electrometer shows a divergence, which remains if I move about the ball in the

hollow of the cylinder or if I touch with it the inner side of the gauze: that is to say; *the electroscopic effect which an electrified body exercises upon a conductor surrounding it is constant within the entire hollow and just as great as when the inner surface is touched* (Faraday). We will now make use of this law.

A piece of amalgamated leather is fastened to the end of an ebonite rod. I place this, together with the electrified flint-glass rod, within the wire-gauze cylinder (B, fig. 20). Now I rub the two together without touching the gauze. The electrometer shows no divergence so long as the rubber and that which is rubbed are inside the cylinder, because the two kinds of electricity neutralize each other in their effects. According to whether I take out the glass rod or the rubber, the electroscope indicates $-E$ or $+E$, and the divergence in the two cases is equally great, *i.e., by friction both $-E$ and $+E$ are generated in equal quantities.*

After this digression, which has made us acquainted with several important electrical laws, we will conclude our investigation of electric density by settling one more question: According to what law does the electric density increase with the curvature of the surface of a conductor?

Here we see three ebonite stands, upon which three hollow balls of 20, 10, and 5 cm. radius respectively are fastened, which radii bear the proportions r_a, r_b, $r_c = 10$, 5, 2·5, or 4, 2, 1. By means of the two wires d_1 and d_2 (a little over 1 metre long), I connect the three balls (A B C, fig. 21), so that they may be

considered a single insulated conductor. Of course, if one ball is charged by the flint-glass rod, the degree of electrification must be the same in all three balls. If now, by means of a small proof-ball, I take a charge

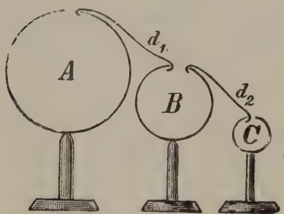


FIG. 21.

from each ball and transmit it to the electrometer, by simply dipping the proof-ball in its hollow ball we get numerical values whose ratio to each other, according to the chosen units of electricity on the scale, must be quite independent, and which will reflect the required ratio of the electric densities.

We find thus:

	A	B	C
Radius of the curvature .	$r = 10$ cm.	5 cm.	2·5 cm.
Observed electric density .	$D = 0{\cdot}6$	1·2	2·5

Hence the ratio is:

$$\text{Electric density } D_a : D_b : D_c = 1 : 2 : 4 \text{ nearly.}$$

Dependence of electric density on curvature.

In A and C the ratio of the radius of the curvature is r_a is to r_c as 4 is to 1; that of the electric densities D_a is to D_c as 1 is to 4, and therefore inversely. Similarly, with B and C, r_b is to r_c as 5 is to 2·5, or as 2 is to 1; on the other hand, D_b is to D_c as 2 is to 4, or as 1 is to 2. From which it follows: when the electric condition of two balls is the same, the electric densities are in inverse ratio to the radius of curvature.

Hence the ratio is:

$$D_a : D_b : D_c = \frac{1}{r_a} : \frac{1}{r_b} : \frac{1}{r_c}.$$

These fractions $\frac{1}{r_a}, \frac{1}{r_b}, \frac{1}{r_c}$ are the reciprocal values of the respective radii of curvature, and establish a

measure of curvature; hence we may say: in spheres of the same degree of electrification, the electric densities are proportional to the radii, or: *if spheres are connected by long thin wires, the electricity is distributed over the outer surfaces, so that the electric densities are proportional to the curvatures of the respective spheres.*

Action of points.

Hence it follows that if, at one part of a charged conductor, the radius of the curvature is very small, and the curvature therefore very great, as, for example, at the point of our conical conductor (such as fig. 14), the electricity must accumulate there in such density that the particles of dust and moisture around must be, in the same way as our proof-ball, very strongly electrified and repelled. When the charge attains a certain strength, the repelling force will be in a position to overcome the resistance of the air, and to throw off the particles of dust and moisture. These bear away with them the neighbouring air particles—others rush into their places, and so arises what is known as the electric wind, the hissing current of air which you perceive at the point of the conductor.

Later on, when treating of the electric machine, we shall make the acquaintance of many interesting phenomena of the action of points; here I must confine myself to showing you the influence which this action of points has upon the charge and discharge of bodies.

Charge by the action of points.

I place a paper electroscope before you and wave the flint-glass rod over the ball at a distance of about 20 cm. The leaves flap to and fro, but—after the rod is withdrawn—the electroscope remains uncharged. Now I fit in the small hole in the side of the ball of

the electroscope a strong piece of wire, bent in the form of a right angle, which ends in a very fine point. This point I cause to turn upwards, and at a distance of about 40 cm. I pass the charged rod quickly over it (A, fig. 22). The electroscope is charged immediately: in other words, the point appears to absorb the electricity.

Action of flames as points.

If I place the second paper electroscope near the charged one, and turn, with an ebonite rod, the point in the direction of the neighbouring electroscope (left in B, fig. 22), we perceive that after a short time the first electroscope (I) gradually loses its charge, while the second one receives some of it. By placing the electrified glass rod on the top of electroscope I (right), the electrification of II may be quickened—

FIG. 22.—Experiment on the action of points, $\frac{1}{10}$ natural size.

we see, therefore, that electricity flows away through points; therefore, in the construction of all electrical instruments, points and sharp edges must be carefully avoided, if it is desired to retain the electricity as long as possible.

If I bring a flame—say that of a wax candle—near a charged electroscope, it loses its electricity very quickly. If I connect by a wire an electroscope with a flame, by fastening it to an ebonite rod, and hold the free end of it in the flame, any previous charge vanishes immediately, and the electroscope cannot be

charged, because all the electricity flows away through the flame. The glowing carbon and gas particles of the flame act like so many fine points, hence the absorbing and dispelling power of a flame is exceedingly great. Now you will understand why we can discharge electrified insulators like ebonite, glass, etc., when we pass them backwards and forwards over a flame, or draw them quickly through it (see note on p. 21).

With this we end our second journey, and next we will try to answer the question: What influence does an electrified body exercise upon its neighbourhood?

CHAPTER III

The phenomena of electric influence. Explanation of the process of influence. Generation by influence of equal quantities of +E and −E. True meaning of the indications of the electrometer. Dual and single-fluid hypotheses. Electrons. Arbitrary zero-point of the scale of electrification. Action of the electric screen. Coulomb's law of electrical attraction and repulsion. Law of influence. What happens when uncharged bodies are attracted by charged ones. Influence the only means of charging.

We have completed two days' journey, during which we have become acquainted with the most important electrical phenomena caused by friction and by direct contact. Last time we saw:

Retrospect. (1) The amount of +E and −E generated by friction are equal to one another. If an insulated conductor is electrified, the electricity is distributed entirely on the outer surface of the conductor, and in such a manner that the electric density is greater the more marked is the total curvature of the particular surface. But no free electricity is to be found in the interior of a charged conductor, whether hollow or solid; or, in other words, the density in this case = 0. On the other hand, the degree of electrification of a charged conductor has the same value over the whole surface, both outside and inside, as in an enclosed hollow space.

(2) If a charged insulated conductor is inserted in the inside of a conductor and connected with it by

means of another conductor, all the electricity passes over to the enclosing conductor. Hence we have a means of transmitting to it the entire charge of a proof-ball and—by repeated introductions of equal charges—of graduating the electrometer.

(3) Since the surface curvature at points is very great, the electricity appears in great density, and by this means a discharge of the body is effected. The incandescent particles of a flame act as very fine points, and the discharging power of the flame is therefore very important, as we can use it to discharge insulators.

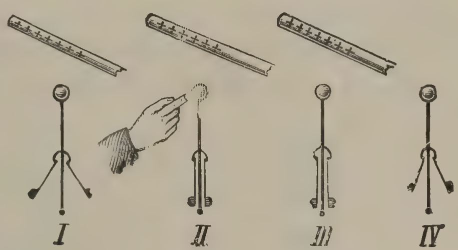


Fig. 23.

The object of our present research will be electrical action at a distance, and to it we shall join experiments on the law of electrical attraction and repulsion. Influence.

In the last chapter we saw that if we move the charged flint-glass rod to and fro over the *un*-charged electroscope, the leaves diverge at every approach of the rod and close up again as it moves away. The electroscope finally remains uncharged. This you have already remarked, but I purposely touched only lightly on these phenomena, so as not to take away your attention from what was then our main object. We will now trace them more accurately.

I repeat the experiment with the positively electrified flint-glass rod, but while the rod is near the electroscope I touch the conducting rod with my hand (II, fig. 23). If I now remove the glass rod

also, the leaves again diverge and the electroscope remains charged (IV). If we examine the nature of the charge, we find, to our astonishment, that the electroscope now contains negative electricity, while the glass rod is still +. Let us now check this experiment by another with the ebonite rod. You see the electroscope now shows + E, while the ebonite rod is negative.

I connect two paper electroscopes (A and B), on which I have screwed balls of 10 cm. diameter,

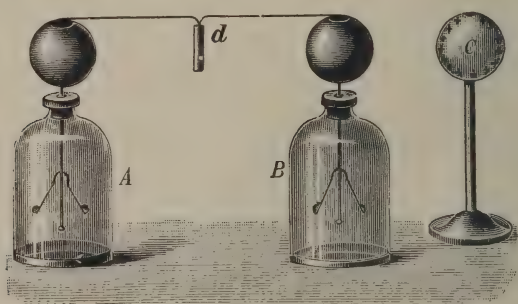


FIG. 24.—Influence experiment, $\frac{1}{10}$ natural size.

by a fine brass wire which has an insulating handle in the middle and its ends bent into loops (fig. 24). Now I bring near B the electrified flint-glass rod or an insulated ball charged with + electricity (C). You see how the leaves in both electroscopes diverge.

First of all, I withdraw the connecting wire (*d*) and then the electrified body (C)—the electroscopes remain charged, and the experiment shows that the nearest electroscope B has the *opposite* kind of electricity to the last-named, namely − electricity, whilst the electroscope furthest away (A) has the *same* kind of electricity (+).

By taking away the connecting wire (d), I intercepted the opposite charges of both electroscopes. If I now again connect both electroscopes by means of the insulated wire, they are discharged. $+E$ and $-E$ must before have been generated in exactly equal quantities.

This peculiar electrical action at a distance is called *electric influence.*[1]

We will therefore call the electrified body causing this phenomenon (in our case the charged insulated ball C) the influencing body.

We see also that an electrified body induces both kinds of electricity in a conductor standing near, and that, too, in equal quantities.

A second check experiment, with a negative charging of the influencing ball, gives the same result, the nearer electroscope being charged with electricity of the opposite kind to the further one which has electricity of the same kind as the influencing body.

Whence now comes the influence electricity of the electroscope B hitherto uncharged? It cannot have come from outside, while the influencing electrified body can have imparted to it only the same kind of electricity that it has itself, and here both kinds of electricity appear. Therefore the influence electricity must have been derived from the uncharged conductor itself, having, however, been induced by the influencing body and, so to speak, called forth by it.

[1] Of late years many physicists make use of the name *induction*, instead of *influence*. But since this word, as we shall see later on (p. 333), signifies a related phenomenon in dynamic electricity, it is altogether more suitable in treating of static or frictional electricity to keep the name *influence* as a distinction.

Process of electric influence.

Nothing else remains to us than to take for granted that in the uncharged body both kinds of electricity were present in equal quantities, and—since no point of it shows free electricity—this electric equilibrium must be present at every point and in every molecule of the uncharged body. With this postulate we can imagine the process of electric influence to be as follows:

(1) The uncharged conductor (L, fig. 25) manifests in every point and in every molecule both + E and − E, which neutralize each other in their external effects (*cf.* p. 18).

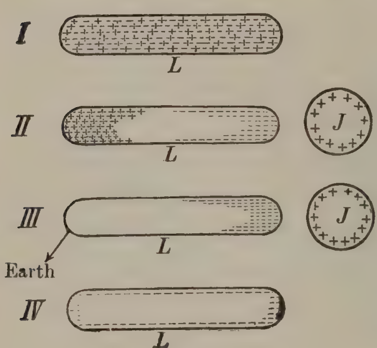


Fig. 25.

(2) By the approach of the influencing, here the positively electrified, body J, the electric equilibrium in the conductor is disturbed, the electricity of the same sign (+ E) being repelled and driven to the end of the conductor furthest from J, while the opposite kind of electricity (− E) is attracted and betakes itself to the end turned towards the influencing body (II, fig. 25).

(3) When touched with the hand the repelled electricity of the same sign as the influencing body flows to earth, while the opposite kind, by the attraction of J, is held back and, so to speak, bound (III, fig. 25).

(4) If we now remove the earth-communicating finger and at the same time the influencing body J, then the opposite electricity which has been bound up

in it ($-E$) must distribute itself over the entire conductor (IV, fig. 25).

The attracted influence electricity of opposing sign is also called "influence electricity of the first kind," and the repelled electricity of like sign, "influence electricity of the second kind" (Reiss, 1858).

The to-and-fro movement of the leaf of the electroscope when an electric body passes over it, is explained by what has been said.

If we replace, in our first experiment (fig. 22), the paper electroscope by the much more sensitive electrometer, the phenomenon is the same. At the same time we may remark: that if the distance of the influencing body from the electrometer ball remains unchanged, the first divergence, which is due to the repelled electricity of like sign, is just as great as the subsequent springing forth of the opposite electricity after the removal of the influencing body. In this case I of course first moved my finger and then the influencing body. On the one hand, also, this is a confirmation of the law found by us, viz., that by influence both electricities are generated in equal quantities; and, on the other, it gives us a ready means of accurately charging the electrometer, or any sensitive electroscope, to any readable degree on the scale, without damaging the delicate leaf of aluminium. In future we will always make use of this manner of charging, but we must not forget that an electroscope charged by influence receives the opposite kind of electricity to what it receives by contact.

We will now perform an experiment which will

increase our knowledge of the nature of electroscopic phenomena, and at the same time teach us to take certain precautionary measures.

Real meaning of the electrometer indications.

I place the electrometer—which, as you see, has a metal case—upon an insulating block of paraffin and connect the outer case by a wire to an electroscope. Now I charge the electrometer with +E and electrify the metal case also with +E. The divergence of the electrometer decreases in the same measure as that of the case increases—it becomes = 0 and increases again; but the test with the ebonite, or the glass rod, indicates a negative electrification of the electrometer. If I touch the case so as to connect it to earth, the leaf of the electrometer falls again and indicates that the original charge was +E. I repeat the experiment by charging the case with the opposite kind of electricity, and now the charge of the electrometer increases continually. What does the electrometer tell us? Seemingly only the difference between the degree of electrification of the leaf and of its surroundings, *i.e.*, the case. In order that the electrometer may show a divergence corresponding to its real charge, the case must also be discharged, and this is done by establishing communication with earth, or, better and more permanently, by taking a wire from it to the water-pipes, which are themselves connected with the earth. This wire which you see running along the wall is called shortly the earth wire, and will be often used by us.

Now we will explain the similar question: Can only a fixed quantity of influence electricity be developed in a conductor, or is the supply of electricity in a conductor unlimited?

For this purpose I charge the electrometer (A, fig. 26), to which I have screwed in a horizontal position a little metal rod ending in a second ball, so that it has a charge of exactly seven units, and then bring it near a very sensitive aluminium electroscope (B) provided with a graduated scale.

You notice how the divergence of the electrometer diminishes, whilst the electroscope (B) originally uncharged evinces a certain amount of charge. If I touch the ball of the electroscope with my finger, the charge of the same sign departs. After removing the finger and taking away the electroscope, it of course shows electricity of the opposite sign, but the electrometer again indicates exactly seven units. I can repeat the experiment as often as I like, and so bit by bit generate an unlimited quantity of influence electricity (+E) in the electroscope (B), without the influencing body losing one atom of its charge. From this we draw the following conclusion :

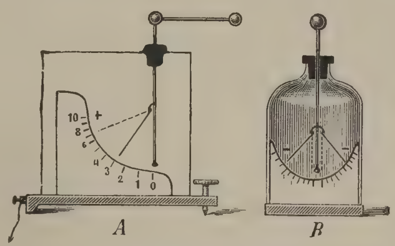


Fig. 26.—Influence experiment, $\frac{1}{7}$ natural size.

An unelectrified conductor (*in this case the electroscope*) *appears either to keep stored up an unlimited quantity of both kinds of electricity, or to be in a position at any moment to make up for the loss of* $\pm E$.

How shall we account for this ?

Since the certainty of the existence of two electric states became evident to us, we have spoken of Hypotheses.

"two electricities," without having any ordered idea of the nature of electricity. We can therefore examine the various phenomena with impartial eyes. Now that we have become acquainted with the most important principles, we will endeavour to form for ourselves an idea of this puzzling force, *i.e.*, we will state an hypothesis, which will explain connectedly all the phenomena observed, without—and this is very important—contradicting any fact which has been noted.

The difficulties which beset us in this matter are greater than in any other branch of physics, because we have no special sensory organ for the perception of electricity. The ear perceives noise, the eye sees the light, and the sense of temperature of the nerves makes us feel when it is warm. But no one organ in nature tells us of the presence of electricity. We see and hear the snapping of the electric spark, and when we approach a knuckle to a strongly electrified glass rod, we feel a peculiar pricking sensation. But all these phenomena might be separately produced by other causes. Only from the continuous, unexceptional combination of all these phenomena do we acknowledge the presence of a common cause, which we name electricity. At this conclusion we only arrive after many observations and specially contrived experiments. Indeed, two thousand years were allowed to pass before electrical phenomena were studied experimentally.

Symmer's two-fluid theory.

Only 149 years have elapsed since Symmer, in 1759, attempted to explain the then known phenomena by the adoption of the *two-fluid or gaseous fluids theory*. According to this hypothesis, sometimes called

the dualistic, every body contains two imponderable[1] fluids, which mutually attract and hold each other, while the atoms of each fluid exercise a mutually repellent force. The expressions we have hitherto used are consistent with this. How does this hypothesis stand examination? The elementary phenomena can be explained by its means, but—what comes from those two combined electric fluids? Whence come the unlimited quantities of both electric fluids which are generated either by friction or by influence experiments? By frictional movement or the approach of an influencing body nothing material can be generated, since movement is only a change of state in the body. We must then drop the dualistic theory. When we hereafter speak of two electricities and of the flow and stream of electricity, we shall do it only in a figurative sense.

Already, some time before Symmer, Æpinus and Franklin (1750) had formulated the *single-fluid hypothesis*, which only recognised one electric fluid, *i.e.*, positive electricity. The dualistic theory held sway until very recent times, and it has still many adherents, as its simplicity is attractive; yet the single-fluid hypothesis has been made the foundation of the modern theories. Single-fluid theory.

According to the single-fluid hypothesis, a body is unelectrified if it contains the same amount of electricity as its surroundings (see p. 50); if it has more electricity than they, it is positively (+E), and if less, it is negatively electrified (−E). *Positive electricity is therefore a superfluity, negative elec-*

[1] In our first experiment (p. 1) we proved that the electrified body neither received nor lost any appreciable weight.

tricity a want, of electricity in comparison with the surroundings.

Analogy between electricity and heat.

You can best represent for yourself the degrees of electrification in the way you usually regard temperature on the thermometer. Some arbitrary degree of heat, that of melting ice, is chosen and marked as zero. The degrees below zero are marked negative and called degrees of cold, although we know that cold is merely a lesser degree of heat. So in electricity we choose an arbitrary zero point—the degree of electrification of the earth—and say: a body contains positive electricity if, when joined to earth, it parts with its electricity to it; and, on the other hand, it contains negative electricity if the converse action takes place.

The fact that by friction or by influence we can generate unlimited quantities of electricity—if we accept the theory of a single electric fluid—forces us also to grant the existence in all space of a certain imponderable substance which immediately makes good in an unelectrified body the loss of $\pm$E. This can be nothing less than the all-pervading, penetrating ether (the light-ether or world-ether). Just as in a large surface of water, elevations and valleys are formed by the waves in endless numbers, when the driving force, *i.e.*, that of the wind, stops them, without the actual quantity of water being increased or lessened, so we can imagine a local thickening and in other places a corresponding thinning of the ether, which conditions the state of electrification in the bodies concerned, or else we must accept a particular kind of wave movement in the ether which is in consequence a carrier of electricity. When electri-

fication takes place, there is thus a transfer of ether movement, which we call electricity, from one place or body to the other. If the body A is rubbed with the body B, and so the first thus becomes positively, and the second negatively electrified, to a certain extent an electric hill has formed in A and in B an electric valley, and yet the sum total of electricity which A and B together have still remains the same. This is also the case in a body in which both electricities are separated by influence—*i.e.*, at one end a superfluity, at the other a scarcity, of electricity is generated. Since, by the union of $+E$ and $-E$, hill and valley again come together and the original level is once more established, so may the process of electrification be repeated as often as desired.

Theory of electrons.

Very lately—on the basis of facts observed in electrolysis, that is, the decomposition of fluid conductors (which we shall study in Part II.)—a theory has been accepted by many that electricity consists of the most minute particles. As to the nature of these electric atoms or *electrons* at present we know very little; still, the view is held that the atoms of the elements are composed of electrons. If the negative electrons are withdrawn from the atoms of bodies, the less mobile ones which are left behind represent the positive electrons, which by union with an equal number of negative electrons form the neutral or *un*-electrified atoms. To take away from a body negative electrons, is to make it positive; to add to a body negative electrons, is to electrify it negatively. As only the negative electrons are supposed to have free movement, the

electron theory seems to approach the single-fluid theory. The negative electrons should be in point of size to bacilli what bacilli are to the terrestrial globe.

According to the Kant-Laplace theory, the primal nebula consisted of similar primary homogeneous atoms, which in the course of millions of years agglomerated by attraction into particles which we now call indestructible, because they are atoms which cannot be divided. The electrons may be primary atoms such as these (Borgmann). According to another acceptation, we need not think that electricity is itself something material, but that the electrons (with regard to their electric charges) may very well consist of local changes in the ether. The chief difference of the new theory from the old consists in the fact that the atomic view is extended to electricity. I cannot go further into this matter, and refer you to W. Kaufmann, "The Development of the Electronic Hypothesis" (*Naturwiss. Rundschau*, xvi., 1901),[1] etc.

The nature of electricity is therefore still unknown to us. The electrical laws observed by us, however, still hold good, as they rest on no hypothetical supposition, but are merely the expression of the way and mode in which electrical forces act upon each other.

[1] See also Professor J. J. Thomson's *Electricity and Matter*, Westminster, 1904, and Mr E. E. Fournier d'Albe's *The Electron Theory*, London, 1906. Excellent summaries of the hypothesis are to be found in Sir Oliver Lodge's Romanes Lecture, *Modern Views of Matter*, Oxford, 1903, and *Electrons*, London, 1906, and Professor Fleming's "Electronic Theory of Electricity" in the *Popular Science Monthly* for May 1902.—*Ed.*

Let us now return to our experiments on electrical action at a distance. The question forces itself upon us whether the condition of the bodies, which are between the influencing body and the conductor, have any effect upon the action of influence.

I charge a paper electroscope (E, fig. 27) with – E, and place near it the large insulated ball, charged with + E, so that through the action of influence the divergence of the leaves is lessened. (In fig. 27 the original position of the leaves is indicated by dotted lines.) Now I place an insulating sheet of glass (*g*) between the influencing body (C) and the electroscope (E)—the effect on the electroscope remains unchanged, as also when I use a plate of ebonite or mica. From this we learn that the electric lines of force[1] penetrate insulators. At first sight this seems extraordinary, but it is no longer so when we remember that the air itself is also an insulator.

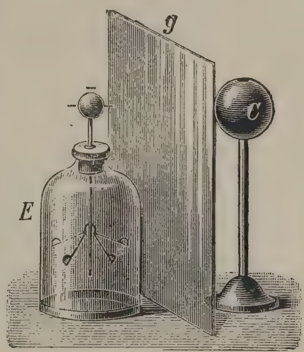


FIG. 27.—Electric effect of screen, $\frac{1}{8}$ natural size.

Now I replace the insulating plane by a sheet of metal. You see how noticeably weaker the influence action of the ball C upon the electroscope becomes. A wire netting of narrow mesh has the same effect.

Still more decisive is the following experiment :—I set the very sensitive aluminium electroscope upon a

[1] By "electric lines of force" we must understand the *direction* in which the observed action at a distance takes effect.

Screen effect of wire-gauze.

metal plate (fig. 28), charge it, and put completely over it a cylinder of wire-gauze, so that the electroscope is surrounded by a conductor. Now I can bring the electrified glass rod as near to it as I like, even so as to draw sparks, and yet the electroscope does not change its condition, while the strips of paper fastened to the gauze do not alter their position.

I repeat the experiment, after having discharged the electroscope—no influence action at all takes place. We may say: The electroscope is in the electric shadow of the enclosing wire gauze. The wire-gauze acts exactly as a screen does against rays of light; that is to say:

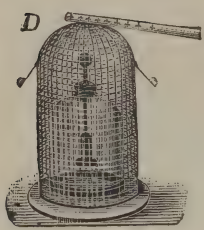


FIG. 28.—Electric guard-cage, $\frac{1}{8}$ natural size.

The electrical lines of force are stopped by conductors, but pass through insulators.

If I lower the influencing body —for instance, an insulated ball— into the inside of a discharged hollow ball, no influence action takes place in an electrometer standing near (Faraday). Should not this electric screen action also have the power of checking the discharging action of flame, *i.e.*, of exercising a negative effect?

I charge a paper electroscope (A, fig. 29) and place a lighted candle near it. You see how quickly the charge of the electroscope diminishes.

Now I adjust a piece of wire-gauze, made into the shape of a half cylinder, in such a position in front of the flame that all the rays of light coming from it which might fall upon the electroscope may be intercepted by the guard-cage. If I now give the

electroscope a charge, it remains unaltered. You will now understand the meaning of the guard-cage of the projection lamp (N, fig. 16, p. 32).

Derivation of the law of electrical repulsion.

We will now set ourselves the task of ascertaining what relationship exists between the force of electrical repulsion between two insulated and similarly electrified bodies and the amount of charge and the distance between the two bodies.

Here you see (fig. 30, p. 60) two spherical and hollow bodies (p and k) made of gold paper, with an

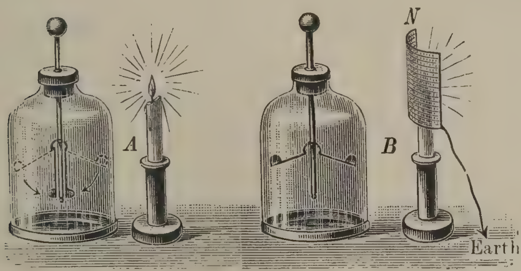


FIG. 29.
A. Action of points of the flame of a candle.
B. Action of the screen of wire-gauze.

opening at the top: of these, p hangs by two long silk threads; the other, k, is fixed to an insulated rod, so that, when in a state of rest, the two balls just touch each other. A millimetre[1] scale placed behind them allows us to measure the lateral deviations of the electric pendulum (p).

By means of an ebonite rod, which I apply to the

[1] The scale consists of a piece of millimetre paper 15 mm. broad, pasted on to a narrow mirror. The horizontal middle line of the scale lies a little higher than the balls. One's point of view must be such that the suspending threads coincide with their images on the mirror.

Influence of charge of influencing body.

silk threads, I push the pendulum (p) a little aside and charge the stationary ball (k) by giving it, with a small insulated proof-ball, a certain number of charges from the conical conductor. Now I let the pendulum slowly fall back—the two exactly equal bodies p and k touch each other and are charged with an equal amount of electricity. Through the electrical repulsion, p is driven away from k, and takes a new position of rest (p', fig. 30). The pendulum (p) has described a small segment of a circle, the centre of which is the suspension point of the two silk threads. The force of terrestrial gravitation draws the pendulum back, while the force of repulsion acts against it. As calculation shows, on account of the length of thread of the pendulum and the small deviation, the angle which is described is very small.

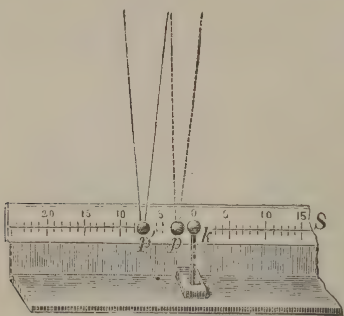


FIG. 30.—Pendulum electrometer (Odstrčil), $\frac{1}{10}$ natural size.

According to the rules of mechanics, inquiry into which at present would carry us too far afield, the action of gravity in this case is proportional to the lateral deviations of the pendulum — this we will measure in centimetres. But since electrical repulsion counter-balances the action of gravity, and so is measured in terms of it, *then the distance between the centres of the balls* (p *and* k), *measured in centimetres, forms a measure of the force of repulsion.*

Let us now begin our experiments. I discharge both balls, and then, in the manner mentioned, I give

to the fixed ball two charges, and consequently after contact each ball receives one charge. The distance between the centres is $d = 5$ cm., and the divergence $a = 3$ cm. I give to k another charge; thus k has in all two charges, p only one—the divergence increases. If I push k about 3 cm. nearer p, then the distance between the balls is 5 cm. and the divergence = 6 cm. from the point of rest. When the charge of k is three-fold (and the distance between the balls is 5 cm.), the divergence is 9 cm., *i.e.*, three times greater. If I repeat the experiment, but give to the pendulum (p) two charges, I get double the divergence we had before, as the following table shows:—

	Pendulum p	Fixed ball k	Divergence a
I. Experiment	1 charge	1 charge	3 cm. $= 1 \times 1 \cdot$ (3 cm.)
	1 charge	2 charges	6 cm. $= 1 \times 2 \cdot$ (3 cm.)
	1 charge	3 charges	9 cm. $= 1 \times 3 \cdot$ (3 cm.)
II. Experiment	2 charges	1 charge	6 cm. $= 2 \times 1 \cdot$ (3 cm.)
	2 charges	2 charges	12 cm. $= 2 \times 2 \cdot$ (3 cm.)
	2 charges	3 charges	18 cm. $= 2 \times 3 \cdot$ (3 cm.)

We can get the numbers in the last column (a) by multiplying the number of charges (p and k) by a constant (3 cm.), which depends upon the amount of electricity used as unit, and is equal to that particular force of repulsion which bodies mutually exert, if each is charged with the unit quantity of electricity. We can consequently state:

The repulsive force of two bodies charged with the same kind of electricity is in direct ratio to the

strength of the charge; and if e and e' denote the charges:

$$a = e \times e' \times \text{const.} \quad . \quad . \quad . \quad . \qquad (1)$$

Effect of distance of the influencing body.

Now we will examine the effect of *distance* on both bodies.

As both hollow balls p and k have a diameter of 2 cm., or a radius of 1 cm., their centres are, when the balls are in contact ($p\ k$, fig. 31), *i.e.*, at rest, exactly 2 cm. distant from each other.

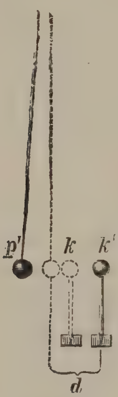


FIG. 31.

I give the ball p one charge, and the fixed one, ball k, four charges. The distance between the balls is $d = 14$ cm. (as unit of distance), and the divergence $a = 12$ cm. Now I push k to the position k', so that the *distance d is doubled*, then $d' = 2d = 28$ cm.: the divergence of p is $a' = 3$ cm. Now I push k further still (about 15 cm.), until the distance between the balls $d'' = 3d = 42$ cm. The stroke a'' (from rest) is 1–3 cm.

Let us again place the result so as to be seen at a glance.

Distance between the Centres of the Balls d	Divergence of the Pendulum (from rest) a
14 cm. $= d$	12 cm. $= \frac{12}{1} = \frac{12}{1^2}$
28 cm. $= 2d$	3 cm. $= \frac{12}{4} = \frac{12}{2^2}$
42 cm. $= 3d$	1·3 cm. $= \frac{12}{9} = \frac{12}{3^2}$

From this we gather: if the distance between the balls increases 1, 2, 3, . . . n times, the divergence decreases, as also the force of electric repulsion proportional to it, as, $\frac{1}{1}, \frac{1}{4}, \frac{1}{9} \dots \frac{1}{n^2}$; *i.e., the repellent force of two similarly electrified balls is in inverse proportion to the square of the distance of the centres of the balls.*

If now the distance of the centres of the balls $= r$, then the force of repulsion is inversely proportional to r^2, or directly proportional to its reciprocal $\frac{1}{r^2}$. We discovered before that the repellent force of two similarly electrified bodies was equal to the product of the two electric charges; hence the entire law of electric repulsion is:

The electric force of repulsion between two balls charged with the same kind of electricity is equal to the product of both quantities of electricity divided by the square of the distance of the centres (Coulomb). Coulomb's law.

If both bodies are oppositely electrified, after mutual attraction, which we can consider as a negative repulsion—

$$\left.\begin{array}{l} \text{in bodies with similar electricity,} \\ \qquad a = \dfrac{e \times e'}{r^2}\text{; or } \dfrac{(-e) \times (-e')}{r^2} = +\dfrac{e \times e'}{r^2}\text{;} \\ \text{in bodies with opposite kinds of electricity,} \\ \qquad a = \dfrac{e(-e')}{r^2}\text{; or } \dfrac{(-e) \times (+e')}{r^2} = -\dfrac{e \times e'}{r^2}. \end{array}\right\} \quad . \quad . \quad (2)$$

This law of electric repulsion was first discovered by Coulomb (1785) in a very laborious way. The experiment made use of above was invented by Odstrčil (Appendix, 7, p. 387).

We have seen that an electroscope surrounded entirely by a conductor is not influenced by an electrified body outside it, and still less so if the surrounding conductor is electrified. In the case of a surrounding hollow sphere, on which the electricity is distributed equally over the outer surface, instead of the law of inverse squares just found, the law is—and indeed only for such—that the influence of the electrified surface on any point of the hollow space = 0. The fact already observed, that electricity lies only

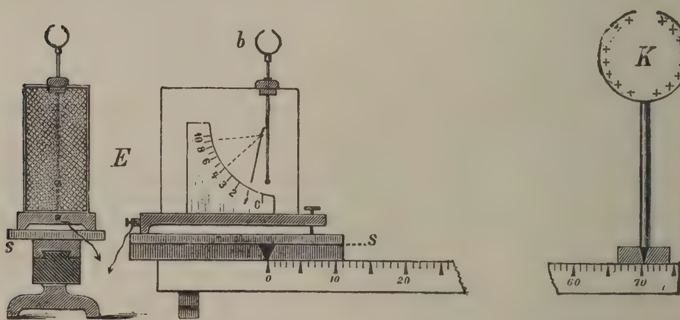


FIG. 32.—Quantitative influence experiment, $\frac{1}{8}$ natural size.

on the outward surface of an insulated conductor, forms the most conclusive proof of the validity of Coulomb's law.

Our present goal is nearly reached. It only remains for us to examine what relationship exists between the quantity of influence electricity and the distance and strength of charge of the influencing body.

I place the electrometer (E, fig. 32) in such a position on the slide S of the optical bench, that the middle point of the electrometer ball *k* is directly over the zero point of the millimetre scale.

The insulated hollow ball (*k*) is exactly the same

height as b. Let k be now strongly electrified and pushed *slowly* towards the electrometer; the little leaf begins to rise gradually—now it is exactly at 1·0. The distance between the balls is 70 cm. If I push k to half the distance $\frac{70}{2} = 35$ cm., the electrometer indicates a divergence of 4·0; that is four times as great. If I place k at a point one-third the distance, *i.e.*, a space of $\frac{70}{3} = 23{\cdot}3$ cm., the electrometer indicates 9·0, *i.e.*, a divergence nine times as great. Since, as we know, influence generates $+E$ and $-E$ in equal quantities, we get for small balls at a great distance from each other the law of squares.

The amounts of $\pm E$ electricity generated by influence are in inverse ratio to the square of the distance. First law of influence.

If I connect the influencing ball k with another insulated ball of the same size, the divergence of the leaf of the electrometer is unchanged. If I remove the connected ball, k keeps only half the charge, and you see the divergence on the electrometer has sunk from 9·0 to 4·5, or only half as great. If I again touch the electrometer with the newly-charged auxiliary ball, the electrometer indicates after its removal still only 2·25, namely, one-fourth of its original value.

The quantity of $\pm E$ electricity generated in an uncharged conductor by influence is in direct proportion to the strength of charge (Electrical quantity, J) of the influencing body. Second law of influence. For the distance, r, consequently the complete expression of the law of influence (strictly speaking, in relation to the distance, in the case of little balls), is:

$$E = \pm k \times \frac{J}{r^2} \quad . \quad . \quad . \quad . \qquad (3)$$

the formula for the amount of electricity (E) generated by influence, where k is a constant factor, depending upon the unit of length (if $r = 1$, $E = k J$).

The law just enunciated gives us an explanation of the principle of the attraction of uncharged for charged bodies.

If p (fig. 33) is one of the electric pendulums used by us in the beginning, and k an electrified body, both $+e$ and $-e$ are generated by influence in the unelectrified pendulum p. The opposite electricity flows to the side turned towards the influencing body and is accordingly nearer to it (r is shorter than r'); hence the attraction which k exercises will be greater than the repulsion; and, in fact, the nearer the influencing body approaches, the more will the attraction preponderate, until finally it will become so great that the resistance of the air will be overcome. The opposite kind of electricity leaves the pendulum p and neutralizes in k a corresponding quantity of electricity of the opposite kind to the influencing body k. In p there accordingly remains like electricity, by means of which the pendulum is now repelled. Hence *there is no such thing as an electric charge by contact, but only by influence.*

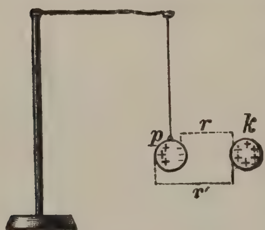


FIG. 33.

And with this we will conclude our to-day's journey; we will consider next the effect which a conductor, brought near an electrified insulated conductor, has upon it.

CHAPTER IV

Action of the plate condenser. Theory of the condenser. Multiplying power of the plate condenser. Graduation of the electrometer with the condenser. The condenser as accumulator. The electric jar. The electrophorus. Determination of the capacity of a Leyden jar. The capacity of a condenser depends on the distance apart of the coatings. Dielectric constant.

DURING our former lessons, we have become acquainted with the principal phenomena which arise from bodies electrified by friction or through influence. To-day we are in a position to make an important use of the laws discovered; but first of all we will summarize the results of our last experiments. Retrospect.

(1) The force of electric repulsion or attraction which two electrified bodies exercise upon each other is in direct ratio to the quantity of electricity of the bodies and in inverse ratio to the square of their distance from each other (Coulomb's law, $\alpha = \pm\frac{e \times e'}{r^2}$).

(2) By the electrification of any body the electrical equilibrium of all neighbouring conductors is disturbed; the opposite electricity is attracted and bound; and the like electricity is repelled. If the conductor is insulated, and—while the influencing body is near—is connected to earth for a second, the free electricity of like sign escapes and the conductor remains,

after the removal of the influencing body, charged with the opposite electricity. The quantities of +E and −E generated in a conductor by influence are equal. This allows very delicate electrometers to be charged to a determined degree.

(3) The action of influence takes place through insulators, but it is checked by conducting screens, and is entirely stopped if either the influencing or the influenced body is entirely surrounded by an uninsulated conductor. The amount of influence electricity is in direct ratio to the quantity of electricity of the influencing body, and in inverse ratio to the square of the distance. Hence it follows that the charging of a body takes place only apparently by communication—that is to say by contact—but really by influence.

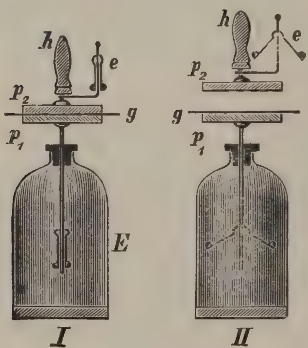


FIG. 34.—Plate condenser, $\frac{1}{10}$ natural size.

We will now examine the action of influence which two flat metal plates exercise upon each other, when very close together, but separated by a layer of insulating material.

Condenser experiment.

I screw upon a paper electroscope (E, fig. 34), in the place of the ball a highly polished metal plate (p_1). Upon this I lay a very thin sheet of mica (g), varnished on both sides, and projecting about 2 or 3 cm. all round the plate. Upon this comes a second metal plate (p_2), similar to the first, and with a handle of ebonite (h), to which a bent piece of stiff wire with a loop at each side of the vertical

part is fastened. This vertical part of the wire bears a small paper electroscope.

If I now charge the lower plate (p_1) by touching it with an insulated proof-ball, which I have charged by the conical conductor (fig. 14, p. 30), the electroscope shows a small divergence. Must the proof-ball have parted with its entire charge? Our electrometer is ready on the little projection table (fig. 16). I screw a small hollow ball on it and lower the proof-ball into its interior. You notice a divergence follows, that is to say, the proof-ball has retained a part of its charge after contact with the metal plate.

I repeat the experiment, but touch at the same time the upper plate (p_2) with my finger—apparently no action follows; yet, the proof-ball indicates on the electrometer a distinct trace of one more charge.

Where has the electricity of the proof-ball remained? I repeat the experiment five or six times—the result is always the same.

The proof-ball, however, when it becomes discharged by contact with the lower plate (p_1), imparts to the latter its entire charge, which cannot pass over to the simultaneously discharged upper plate, since an insulating plate is between the two; yet the electroscope shows no trace of charge. But if I now lift up the upper plate (p_2) by the insulating handle, you perceive that both plates are strongly electrified (II, fig. 34). A test shows that the lower plate has the same electricity as the proof-ball; the upper one the opposite.

Here, of course, there is an action of influence. The electrified lower plate acts the part of the influencing body, the upper one that of the insulated conductor.

While the plates—insulated by the sheet of mica—rest one upon the other, the electricity on both of them is in the state which in the last lecture we called "bound." We can for the present only accept the fact that the mutual attraction of the two opposite electricities, when in close proximity, is so strong, that they not only both lose their free movement, but also strive energetically to approach each other. Hence it comes about that they must gather exclusively upon the surfaces of the two plates which face each other; hence the upper parts of the plates, as also the conducting rods with the leaves, no longer receive any free electricity. And thus is explained the apparently uncharged condition of the two electroscopes (E and *e*, fig. 34, I) before the lifting up of the upper plate.

Now comes the question: Is the binding of the electricities which is brought about by the very close proximity of the two plates complete or not? Let us take the first case. Consider that the −E of the upper plate generated by influence could bind the entire +E of the lower plate. What would the result be? Evidently in such a case—whilst the upper plate is connected to "earth"—the lower plate would show no electricity. Further, when both plates are alternately touched by the hand, no loss of electricity should result, and so the charge would not diminish. This we may confirm by experiment.

I give the lower plate a stronger charge than before, at the same time connecting the upper one to earth. You see how, after a certain greater number of charges, the leaves of the *lower* electroscope diverge *slowly*,

thus showing a continually increasing charge of electricity; while those of the upper plate remain in a state of rest (A, fig. 35). If now I touch the lower plate, the leaves collapse, whilst those on the upper plate rise up (B, fig. 35).

When the upper plate is lifted up, both electroscopes exhibit a very great divergence. But if I continue alternately touching the plates, bending the thumb and forefinger in the form of a C, so as to embrace the edges of the plates without touching them, and thus touch first with the thumb the under

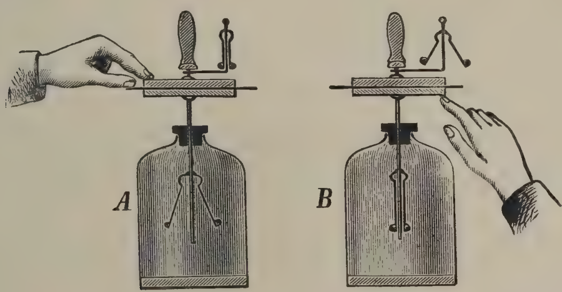


Fig. 35.—Action of the condenser.

plate and then with the finger the upper one, the divergence of the plate not immediately touched diminishes, and after the removal of the upper plate both electroscopes indicate a much weaker charge.

We see from this that our first supposition, namely, that the electricities of both plates could completely bind each other, was not right. As long as the plates were only separated by the thin sheet of mica, the electricities are found to be accumulated in a dense and in a certain measure a *condensed* state upon the two inner (*i.e.*, turned towards each other) surfaces of

the plates. Hence a pair of plates, separated by a layer of some suitable matter, is called a *plate condenser*, or, shortly, a *condenser*.

Theory of the condenser.

How shall we conceive this action of the condenser? We observed that the upper plate, separated from the other by only a thin sheet of mica, when connected to earth, was able to "bind" the greater part of the charge on the lower plate. Let us suppose that the lower plate is able to receive a charge of L units, in order to reach a certain specified degree of electrification, and that the super-imposed plate, connected to earth, has the power of "binding" a certain determined fraction (x) of the charge L of the lower plate. Let this fraction $= \frac{99}{100}$.

Therefore, *on the lower plate* of the original charge L there are now bound $x\text{L} = \frac{99}{100}\text{L}$, while there are free only $\text{L} - x\text{L}$, that is, $\text{L} - \frac{99}{100}\text{L}$, that is, $\frac{1}{100}\text{L}$. The ratio is

$$\frac{\text{original charge of the (lower) plate}}{\text{free electricity of the (lower) plate}} = \frac{\text{L}}{\text{L} - x\text{L}} = \frac{\text{L}}{\text{L} - \frac{99}{100}\text{L}} = \frac{100}{1}$$

that is to say, in order to charge, when the upper one is connected to earth, the lower plate up to the original degree of electrification, we must add a quantity of electricity 100 times greater than before. Hence the *electric capacity of this plate has increased a hundredfold.* This number (here 100) is called *the multiplying power of a condenser.* Therefore

$$\text{the multiplying power of the condenser} = \frac{\text{the capacity of the plate as condenser}^{1}}{\text{capacity of the same plate alone}}.$$

[1] With regard to the same degree of electrification of free electricity.

Let k represent the multiplying power of a condenser; then, according to the above,

$$k = \frac{L}{L - xL} = \frac{1}{1 - x}.$$

If we succeed by experiment in finding the number x (the ratio of the bound electricity to the original charge), we can easily calculate the multiplying power of the condenser (*cf.* Appendix, 8, pp. 387–389).

The condenser may now be of use in accumulating very weak electric charges, which cannot even be indicated by the very delicate aluminium electroscope, and in so strengthening their action that they can be registered by the electrometer. Later on, in the study of galvanism, we shall make use of the condenser, discovered by Volta, in a very important matter. Condensers are, therefore, in the true sense of the word, apparatus for the accumulation of electricity. As in the present case the quantity of free electricity is comparatively small, so also is the loss of electricity in the case of a closed condenser, that is to say, if the plates are only divided by an insulating layer, it is very insignificant, and in this way an electric charge may be kept for several days.

We have already seen that when two bodies are electrified with equal amounts of electricity, no electricity passes over from one to the other. From this follows this result, which has a most important bearing upon electric measurements: *a condenser can only be charged to such a point that the* not *bound electricity on the immediate electrified plate has the same degree of electrification as is indicated by the source of electricity used.*

As we shall have to make great use of condensers, it is of interest to discover how great is the multiplying power of the particularly carefully constructed plate, which we shall use for our measurements, and which we shall therefore call our *normal condenser*. Ground to the utmost evenness, it is nickel-plated throughout, and its inner surfaces and edges varnished with a very thin and regular coating of shellac. By this means the multiplying power of this normal condenser is rendered very great.

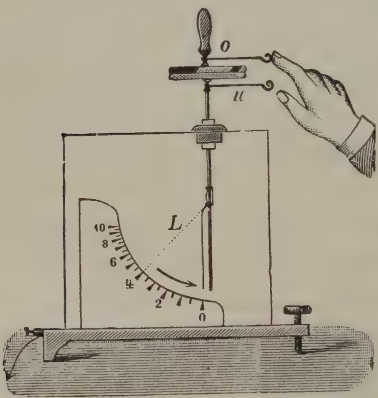


FIG. 36.—Electrometer with condenser, $\frac{1}{5}$ natural size.

Multiplying power of the condenser.

I screw a plate on the electrometer, the case of which — as in all measuring experiments — is connected to earth (fig. 36). Now I give the electrometer, by influence, a charge L of 4·0 scale units. If I now put on the upper plate, insulated by means of an ebonite handle with a nickel-plated conducting wire (0) attached, and connect it to earth by touching it, the leaf of the electrometer falls almost completely down.

If you observe carefully the end of the leaf on the projection screen, you see that it takes up a position between 0 and the first tenth—nearly $\frac{1}{3}$ of this space, about 0·03, therefore corresponding to $\frac{3}{100}$ of a scale unit. (If I touch the lower plate, the leaf retires quite back to 0.) You see from

this that the amount of free electricity was extraordinarily small. We get as multiplying power of the condenser :

$$k=\frac{4\cdot 0}{0\cdot 03}=\frac{400}{3}=133.$$

A more exact calculation (Appendix, 8, p. 389) gives $k=200$.

Let us imagine a prolific source of electricity of so small a degree of electrification that no appreciable charge follows direct touching of the lower plate (such a source of electricity is, for instance, described in the second part on *Galvanism*); then we can, by the use of the condenser, bring the free electricity to this degree of electrification, and after lifting up the upper plate get a degree of electrification two hundred times as great, which is easy to verify. You will gather from this, that under certain circumstances, by the employment of the condenser, the sensitiveness of the electrometer can be increased two hundredfold.

The quantity of electricity generated by influence in the earthed upper plate, is, as we see, in a particular ratio to the charge of the fixed plate. This ratio depends upon the multiplying power of the plate in question. As we can now charge an electroscope exactly, by influence, to any point on the graduated scale, the upper plate of the condenser connected to earth, and then removed, yields always the same amount of electricity so long as the lower plate keeps its original charge; and of this we can easily convince ourselves by observing from time to time the divergence of the leaves.

A condenser may therefore also be used as a very good source of electricity, in order, by means of

another conductor, to graduate the electrometer. This method has further the great advantage that brass, when the air is comparatively dry, is not disturbed by loss of electricity; as in the case of a closed condenser, the free electricity, as also the loss of electricity, is quite imperceptible.

Graduation of the electrometer by the condenser.

I place an aluminium electroscope (A, fig. 37), fitted with a condenser, near the electrometer. The electroscope must have been well tested and possess

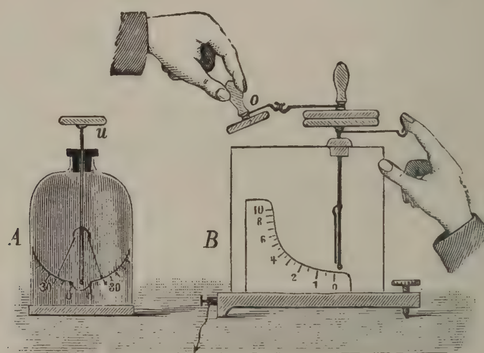


Fig. 37.—Graduation of the electrometer, ½ natural size.

especially good insulating qualities. I charge it with +E by influence, put on the upper plate (o), connect it to earth by touching it, and transmit its charge to the condenser of the electrometer in the manner illustrated by B, fig. 37.[1]

After lifting up the top plate, the electrometer shows a certain divergence α_1, which stands in a determined ratio to the charge of the electroscope A; and by this then it may be regulated. If, in this

[1] The charge of the plate (o) might just as well have been transferred to the lower plate of the electrometer, by touching the upper plate to connect it with earth, and this is the more practical way.

way, I give the electrometer 2, 3, 4, etc., charges, I get a divergence on the electrometer, representing 2, 3, 4, of the electrical units chosen. *In this way our projection scale of degrees originated*, and by its means, but some time after, a more accurate unit was adopted as the degree of electrification, namely, the measure in units of work (*vide* Chapter VI.) of what is called a *volt*, in honour of Volta, the physicist. Our scale of degrees is, therefore, when the normal condenser[1] is employed, at the same time a volt-scale.

We have already learned that a condenser, even when the insulation is perfect, can only be charged to such a point that the unbound electricity on the electrified plate has received the same degree of electrification as was possessed by the source of the electricity used. By the action of the condenser it is possible—as we have already seen—to increase by artificial means the capacity of the plates. So far, by this method, we have accumulated only very small quantities of electricity. We can, however, use larger amounts of electricity, but the insulating plate must be sufficiently thick, in order to hinder the electric sparks from flashing through it.

Action of the condenser.

I make use of the same brass plates as in our first ex-

[1] The multiplying power of the condenser is not constant, but dependent upon the amount of moisture in the air; hence our volt-scale, considered from the point of accuracy, is only valid for the then condition of the condenser. But for this reason the scale is always available as a graduated scale for other condensers. If we wished to give the observed degree of electrification in volts, it would be merely necessary to determine the divergence which a *volt* brings out, *e.g.* 0·85; then the fraction $\frac{1}{0{\cdot}85}$ would be the reduction factor with which the value obtained must be multiplied.

periment (*cf.* p. 74), but I place between them a piece of mica varnished on both sides and 1 mm. thick, which overlaps the plates of the condenser all round by about 2 or 3 cm. Whilst I connect the upper plate to earth by touching it, I charge the lower one with the electrified flint-glass rod, by putting this on the conducting rod of the electroscope (fig. 38) and taking it away again. I repeat this about ten times. You see, the leaves of the electroscope indicate continually more and more free electricity. If I now move away the upper plate in as steady a manner as possible, I can draw from both plates a plainly visible and audible spark, by putting near them the knuckle of my first finger. I again repeat the experiment several times, and beg you to touch at the same time both plates of the closed conductor. You feel a pricking sensation in the finger tips, more marked than that obtained by the discharge of the spark from the plate taken away.

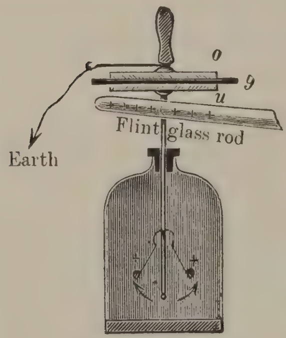


FIG. 38.

If we require to arrange this kind of condenser in a simpler form, we need only paste tinfoil on both sides of a well-insulating sheet of glass, being careful to leave a free edge all round (Franklin's plate); but such pieces of apparatus are very fragile. A more practicable form of condenser for large amounts of electricity is the electric jar, discovered in 1745 by Kleist, and by Cunäus in 1746, in Leyden, also known by the name of the Kleist or Leyden jar.

I put before you a dismountable example of one of these electric jars, from which we can learn in a convenient way their action (fig. 39).

Electric jar with movable coatings.

A closed metal vessel (i), provided with a strong conducting rod ending in a ball, fits exactly into a well-insulating glass beaker (g), and this in turn into a metal vessel (a). B, fig. 39, shows the electric jar fitted together. The metal cover a is called the *outer* and i the *inner coating.*

I charge the jar by repeatedly (15 or 20 times) placing the electrified glass rod[1] on the ball of the

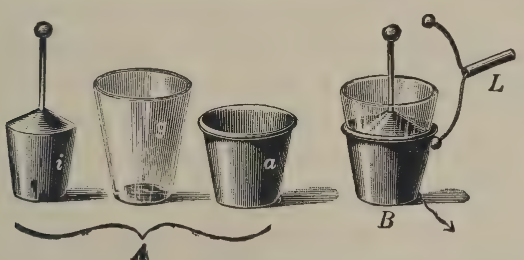


FIG. 39.—Electric jar with movable coatings, $\frac{1}{12}$ natural size.

conducting rod, and draw it along so that as great a part of its surface as possible may come in contact with the metal; at the same time I touch the outer coating with the other hand, or I fasten the earth wire to a hook in the outer coating. If I now first touch with the *discharging tongs* (L, fig. 39) (this consists of a strong wire with the middle loop mounted in an insulated handle, the ends of the wire terminating

[1] The flint-glass rod referred to here (a present from my departed colleague, Chamonton, who brought two specimens from Greenwich) is about 40 cm. long, and its action is very strong. After being rubbed with amalgamated leather, it yields sparks 4–5 cm. in length, when brought near the knuckle. It has a convenient wooden handle, to obviate contact.

in metal balls) the outer coating, and then apply the other ball to the ball of the jar, you hear a sharp report and see a bright spark shoot across.

Would you like to test the action of this condenser? While I again charge the jar, form a chain of three or four persons, by taking hold of each other's hands. Let the first person in the row lay hold of the outer coating of the jar. Let the last touch with the knuckle (not the finger tips) of his bare hand the ball. You all start, because the electric shock went through your bodies, and attacked with a kind of a cramp the muscles of your hand and arm as far as the elbow. This is a small jar. The larger one on the side-table yonder can be still more strongly charged. The glass vessel has the shape of a cylinder, and is pasted over outside and inside for $\frac{3}{5}$ of its height with tinfoil. The conducting rod is insulated from the wooden cover by means of an ebonite stopper, which gives better results and protects the inside from dust. The lower end of the conducting rod is provided with three narrow, feather-like strips of metal, which make a conductive connection with the inner coating of tinfoil. In order to increase the insulating power, the uncoated glass surface, after being thoroughly warmed, is painted over with shellac varnish.

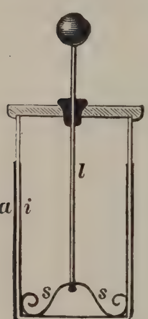


FIG. 40.—Large electric jar, $\frac{1}{15}$ natural size.

Before we pursue further the enquiry into the action of electric or Leyden jars, we must seek for a means of generating in a more convenient way a larger amount of electricity than is possible with the

flint-glass rod. Such an apparatus, which at the same time shows us an interesting application of influence electricity, is the electrophorus (Wilke, 1762).

I take an ebonite disc of 5–6 mm. thickness, the upper surface of which has been scoured with glass paper,[1] and the under surface pasted over with strong tinfoil. The electrophorus.

I place the ebonite plate (E, fig. 41) on a metal plate somewhat larger than itself (p), and flick it with a fox - brush. Then I place a hollow disc of metal with rounded edges and an insulated handle on the electrified ebonite plate, and take it away again—it is *un*-charged. If I touch this plate, called the cover of the electro-

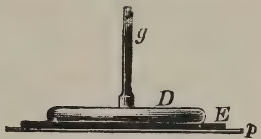


FIG. 41.—Electrophorus, $\frac{1}{10}$ natural size.

[1] This scouring of the ebonite sheet with sand or glass paper (emery paper must not be used, as it injures the surface of the ebonite) has a double object. On the one hand, a smooth surface must be obtained, because thus it becomes more strongly negatively electrified (p. 13), and also the oxidised conducting surface must be removed. Most varieties of ebonite exhibit this very annoying oxidation in the air; others—which cannot be distinguished outwardly—have this quality in a much lower degree: *e.g.*, the ebonite cork of our aluminium electroscope (A, fig. 37), although in constant use since 1887, still insulates perfectly; on the other hand, the insulating quality of the ebonite stopper in the electrometer and the paper electroscope has gone off very much during the course of the year.

Professor Weinhold's proposal to insert in the ebonite stopper an amber tube, somewhat longer than itself, has fulfilled his expectations, so that all electroscopes here used are fitted with it. Copal varnish also insulates perfectly, but it often cracks and is difficult to use; so is the very much recommended mixture of melted paraffin and flour of sulphur.

phorus, while it lies upon it, with my hand, we hear a crackling, and the cover, when again raised up, is strongly electrified with positive electricity. Still stronger is the effect if I touch the lower metal plate (p, fig. 41) and the cover lying on it at the same time. Try it now—a small shock follows, which reminds us of the discharging of the Leyden jars, and, as we shall see immediately, depends upon an allied phenomenon. The cover is now when removed still more strongly electrified, so that when the knuckle approaches it, it yields rather sharp sparks of 3–4 cm. in length.

Its action. What now was the effect of touching both plates at the same time? The strongly negatively electrified ebonite plate generates by influence on the cover and at the same time on the lower metal plate $\pm$ E. The repelled $-$E of the cover can only escape by being earthed or by touch, but the $-$E of the lower plate flows through the table to the earth. Accordingly, the bound $+$E remains and acts in its turn upon the cover, whereby the charge of this last is diminished. If now both plates are conductively joined, the free $-$E of the cover unites with the weaker bound $+$E of the lower plate (on account of the greater distance from the electrified upper surface); thus the hitherto bound part of $-$E on the electrified surface becomes free and strengthens the influence action on the cover. That the process occurs in this way appears from the following experiment. I again place the re-charged cover in position, and touch it to connect it with the earth. Kindly touch it again. You feel no further charge. Now hold your finger tightly on the cover, and at the

same time touch the lower plate (p). You feel a distinct shock, although not so strong as before. The reason lies in the fact that the bound + electricity on the lower plate used your hand as a bridge, in order to betake itself to the lower surface of the cover, and thus get as near as possible to the $-E$ of the ebonite surface. Why do not the electricities of the cover and the electrified disc unite, since both surfaces are in contact? Well, because an insulator only parts with its charge under compulsion.[1]

Every surface, also, even the smoothest, has small elevations, so that the cover of the electrophorus rests, in a certain measure, on insulated points. At the outset the charge of the ebonite plate diminishes a little; later on so very little that—if the cover set on it is connected to the earth—an electrophorus, when the atmosphere is dry, keeps its charge for weeks together.

The original electrophorus plates consisted of fused lumps of resin, but these, on account of their fragility, were not very suitable; in summer also they were very easily bent.

Let us now return to our Leyden jar experiments. Let us charge the dismountable jar (fig. 39)—ten charges with the cover of the electrophorus will suffice. When discharging it with the discharging rod (fig. 39), a very bright spark appears, accompanied

[1] To discharge an insulator fully it is not sufficient to pass it through a flame, as most teachers say, but it must be rinsed in clean water, rubbed with a linen cloth, and then carefully dried before a steady flame (in the case of condenser-plates, until the film of moisture which forms at first quite disappears). It must then be allowed to cool.

by a very loud report, as in the last experiment. Now, after the jar is discharged, I tap with my pencil on the glass vessel, and we can draw another charge, although a very weak one. We could have done the same without tapping if we had allowed it to stand a long time.

Residual charge.

How shall we explain this remaining charge, this so-called "residual charge"?

I place the dismountable jar upon a well-insulating block of paraffin and fasten to the conducting rod a strong silk thread. Now I electrify the jar as before, of course connecting with the hand the outer coating to earth, and by means of the silk I lift out the inner coating. When a paper electroscope is touched with it, it indicates only a small charge of $+E$.

Now I lift up the glass vessel and touch the insulated outer coating with the head of the re-charged paper electroscope—there is scarcely a sign of electricity visible. *But if I put the jar together again, there appears, when the discharging rod is applied to it, a brilliant spark, and the loud sound accompanying shows that the electric jar had kept its charge.*

Evidently that part of the charge hitherto called by us "bound" had betaken itself to the surface of the glass.

Now we know (see note, p. 83) that insulators only part with their full charge with difficulty, and as the spark discharge takes place in such an extraordinary short space of time that all the electricity cannot follow quickly enough, it happens that a residuum remains. Gradually a part of the electricity remaining on the surface of the glass betakes

itself to the coating (and this is called forth by tapping), and when the discharger is brought very near it yields a spark. According to this, it is probable that a discharging jar, after a long rest, will yield another charge or several charges of diminishing strength. This actually happens.

I now charge the large electric jar (fig. 40), the conducting rod of which I have connected with a paper electroscope by means of a wire. I then place one of the balls of the discharger on the outer coating and slowly bring the other one near to the ball of the jar. When a certain distance off, several sparks flash across, accompanied by a loud crack. Bringing it nearer still, several more sparks flash across, the strength of which apparently diminishes very quickly. At every discharge, of course—as the sinking of the electroscope leaf shows—the amount of stored-up electricity decreases, hence the *electric density* grows less; accordingly the force is no longer sufficient to overcome the resistance of the air. Only when the balls are brought nearer can another part of the charge be discharged by a spark. After what has been said, it is clear that when a discharge occurs by means of a spark, the residual charge of the jar must be greater the greater the length of the spark. On the other hand, the remaining charge of the electric jar, the "jar-residuum" which is left after quick conductive contact of both coatings, depends upon the nature of the glass.

We will now try to gain an idea for ourselves of how great a quantity of electricity an electric jar can store up, in comparison with an insulated conductor

of the same shape and size as the inner coating, when both are electrified to the same degree.

As a testing body we will make use of the inner coating of the portable jar, which is suspended (J, fig. 42) by two strong silk threads (*s*).

A paper electrometer consisting of the electrometer-case and scale already used, but bearing another ebonite stopper with amber tube, while the conducting rod carries a paper leaf instead of an aluminium one, which would be too delicate for the present object,

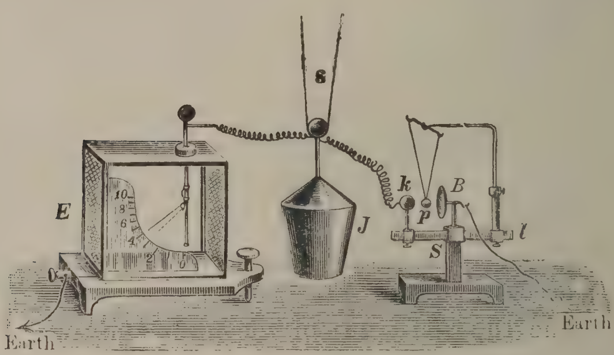


Fig. 42.—Comparison of capacity: S = capacity-measurer, E = paper electrometer (on projection-table, fig. 16). Distance between E and J, also between J and K, 100–150 cm.

will serve to measure the degree of electrification.

Capacity-measurer.

Further, we make use of the capacity-measurer (fig. 42), which is in fact a simple discharging electrometer. A wooden stand (S) bears a horizontal ebonite rod (*l*), together with a firm, thin, nickel-plated disc (B) and a movable ball (*k*). B is connected to earth, and the ball *k* with the body (J) to be tested. Between both there hangs by two very fine silk threads the small electric pendulum (*p*), which measures in diameter 10 mm. and is made out of sunflower pith. It is

covered over with aluminium leaf, stuck on with white of egg.

As soon as I charge the body to be tested (J) with the glass rod, the pendulum (p) between the ball (k) and the plate (B) begins to swing to and fro, and, striking on the plate, it gives out a clear sound, enabling you to count strokes of the pendulum; while on the projection screen, by observing the leaf, you can follow the lessening of the degree of electrification.[1]

I continue charging the body to be tested until the divergence of the leaves indicates more than 4 degrees on the scale. At the moment when the divergence is exactly 4, I give a sign, and you must begin to count the swings of the pendulum, until I give a second signal that the degree of electrification is exactly 3. How many pendulum strokes have you counted? 15. Then 15 discharges of the pendulum ball were necessary to reduce the degree of electrification of the body to be tested from 4 to **3**, *i.e.*, to lower it one unit.

As a comparison, I replace the insulated coating (J) by the insulated hollow sphere of a radius of 10 cm., which we have already used (fig 21, p. 40). In this case 19 discharges are required to lower the electrification from 4 to 3, whilst in the case of a ball of 5 cm. radius 10 discharges suffice.

Now let us again put together the electric jar, and, as before, connect the inner coating with the paper electrometer and the ball k (fig. 42), *while the outer coating is connected to earth.* I begin to charge the inner coating. You already notice that a great many

[1] Of course I might hold an insulated proof-ball to the ball of J, and discharge it with the other hand, but the capacity-measurer is more convenient.

more charges of the glass rod are necessary to electrify the jar up to the same degree as for the inner coating only. Counting the oscillations of the pendulum is now rather tiring. We will begin again, when the divergence is exactly 4. Now—I count aloud up to 10, making a mark on the blackboard every time I reach that number; after every fifth I place a thicker stroke. Now the degree of electrification has reached 3. I hold the blackboard up. How many chalk marks do you count? 27. Therefore we have $27 \times 10 = 270$ discharges. We get, therefore, for the same difference in the degree of electrification[1]:

From the insulated inner coating .	15 discharges.
,, ,, electric jar . . .	270 ,,
,, ,, insulated ball ($r = 10$ cm.)	19 ,,
,, ,, ,, ,, ($r = 5$ cm.)	10 ,,

From this we see that the electric capacity of our small Leyden jar is $\frac{270}{15}$ or 18 times greater than the capacity of the insulated inner coating, and $\frac{270}{19}$ or 14 times greater than that of the insulated ball of 10 cm. radius.

Further, we remark that the ball of 10 cm. radius has almost exactly a capacity twice as great as the ball of 5 cm. radius. Now $10 : 5 :: 2 : 1$, *i.e.*, the capacities of the balls are proportional to their radii. Hence it follows that if (*e.g.*, in the experiment, fig. 12, p. 26) an insulated ball increases its radius 10 times, the volume increases 1000 fold, the surface 100 fold, but the electric capacity only 10 fold.

[1] The exact value appears if we first calculate the capacity of the wire connecting the capacity-measurer with the electrometer and subtract this from the value obtained.

We cannot perform the experiment very well with the large electric jar, as the discharge would take too long. In an experiment made beforehand, 32 minutes were required, in which altogether 154 discharges per minute took place (the strokes occurring during the first minute were counted, and then after every 5 minutes those during one minute). The number of discharges was, therefore, $32 \times 154 = 4928$. Now, the capacity of the great electric jar is $\frac{4928}{19} = 259$ times greater than that of the insulated sphere of 20 cm. radius, *i.e.*, it corresponds to the capacity of a ball of $259 \times 20 = 5180$ cm. or 51·8 m. diameter. You will now understand what an immense charge must exist in a big electric jar charged up to its full capacity.

Leyden jar as constant source of electricity.

In the interior coating of a large electric jar, whose outer coating is connected to earth, we now know that there exists a very continuous supply of electricity, which (*cf.* pp. 30 and 76) is very suitable for the graduation of electrometers.

In conclusion, we will now answer the question: *In what relation does the capacity of a condenser stand with regard to the distance apart of the plates, and what is the effect of the employment of an insulated plate instead of the separating stratum of air?*

The air condenser.

On the optical bench (O), graduated in millimetres, two movable ebonite pillars (l_1 and l_2, fig. 43) are arranged, and through the tops of these brass rods are pushed, to which the two large plates (p_1 and p_2) before used are screwed. The wires are conductively joined to the two paper electrometers A and B. The pillar l_1 I place exactly over the zero point, and move l_2 forward so that the two plates just touch, and then

I fix the pillar l_2 with the screw. If now the pillar l_1 is pushed to the right, we can calculate the distance between the plates to the tenth of a millimetre.

Next I move the movable plate p_1 as far away as possible (*i.e.*, 2 metres) and charge the electrometer A so strongly that the divergence covers 10 units of the graduated scale. Now I again push the electrified plate (p_1) forward, until the distance between the two plates is just 8 cm. :—the divergence on the electro-

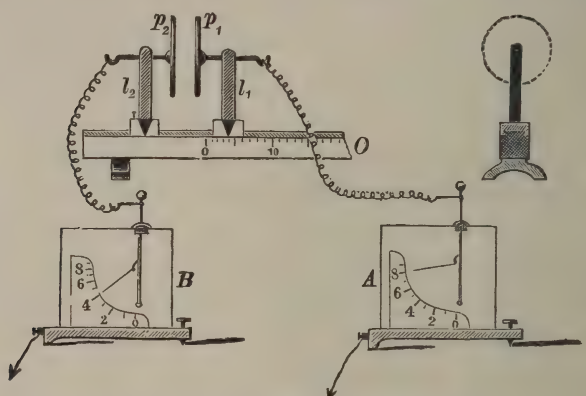


FIG. 43.—Air condenser, $\frac{1}{10}$ natural size.

meter B = 0·6. If I move the plate to half the distance, 4 cm., B shows the divergence = 1·30. Here we immediately remark that in electrometer A the free electricity diminishes in proportion as the opposite electricity in the plate p_2 is bound in B, and the like amount of similar electricity in B electrometer is repelled. Let us continue this and put the results side by side, and we see :—

Distance of plates . .	8 cm.		4 cm.		2 cm.		1 cm.
Influence charge of electr. B .	0·6		1·3		2·7		5·5
Ratio of the charges	1	:	2·2	:	4·5	:	9·1
					$\underbrace{}_{1 \,:\, 2 \text{ nearly}}$		

i.e.: *In plate condensers—for short distances—the capacities are almost in inverse ratio to the distance of the plates.*

I now put before you a very smooth, round paraffin plate, of 18 cm. diameter, and about 2 cm. thick, with an ebonite handle inserted in the side. I hold it close to the plate p_2 (fig. 43), and push the newly discharged plate p_1 along until it touches the other. We read on the index of pillar l_1, that the distance between the plates $= 1{\cdot}80$ cm., and this is the thickness of the paraffin plate, which I again withdraw.

Now, we will compare the action of this paraffin plate (which, as is necessary, overlaps the metal plate all round about 3 cm.) with a stratum of air of the same thickness.

Meaning of the dielectric constant.

I push the plate (p_1), fig. 43, far away, unfasten the wire hook from the electrometer A, and hook it on to the earth wire, so that the plate p_1 is in constant connection with the earth. Now I place the large Leyden jar already used (fig. 40, p. 80) near the other plate (p_2), connect the outer coating to earth, and join the inner one by a short fine copper wire, whose ends finish in loops fastened to small pieces of ebonite, with p_2. I charge the Leyden jar with the electrophorus cover, until the electrometer B shows divergence $\alpha_0 = 1{\cdot}0$. Now I push the plate p_1, which is connected to earth, forward, until the distance between them is exactly $1{\cdot}80$ cm. (the thickness of the paraffin plate), and the electrometer B connected with a very prolific source of electricity indicates scarcely a trace of any decline of divergence. But if I now remove the connection with the electric jar, and push p_1 far back, the electrometer shows a greater

divergence, namely, $\alpha_1 = 3{\cdot}4$. Now I again restore the connection with the electric jar and place the paraffin plate as before on p_2 and push up p_1 again until the two touch. After interruption of the conductive connection with the jar and pushing back the plate p_1, the electrometer (B) shows a still greater divergence, namely $\alpha_2 = 6{\cdot}0$. When the air stratum was used, p_2 was only 3·4 of an electric unit, but in the case of an equally thick plate of paraffin 6·0 units. The action of an insulated cake of paraffin is 6 ÷ 3·4 or 1·7 times greater than that of an equally thick stratum of air.

This quotient

$$\frac{\text{capacity of the condenser with the insulator}}{\text{capacity of the same condenser with an air stratum}} = k$$

is the dielectric constant of the insulator or dielectric. This means that if the capacity of the same condenser with air as the insulating stratum = 1, then the capacity of an equally thick layer of the insulator in question is k times as great.

Therefore, according to more accurate measurements than ours,

The dielectric constant (air = 1) is for

Sulphur	3·84	Vacuum	0·999410
Ebonite	3·15	Hydrogen	0·994764
Glass	3·013 – 3·243	Carbonic acid	1·000356

We learn, therefore, that with respect to those quantities of electricity which are generated by influence, not only must the distance of the influencing body from the influenced one be considered, but also, in a high degree, the nature of the surrounding dielectric (Faraday).

Later on, when experimenting with the influence machine, we shall make the acquaintance of an interesting quality of a fluid dielectric.

The goal of this part of our journey is reached; we have become acquainted with the principal phenomena of static or frictional electricity, and we shall now study the apparatus for the generation of larger quantities of electricity—that is to say, the electric machine.

CHAPTER V

Frictional electric machine and experiments with it. Its theory. Distinction between +E and −E. Experiments with larger quantities of electricity. Electrical induction. The electric field. Electric equipotential surfaces and electric lines of force. Atmospheric electricity. Measurement of atmospheric electricity. Theory of the storm. The lightning conductor.

Retrospect. WE have just made the acquaintance of apparatus for the accumulation of electricity—plate condensers and Leyden jars—and have studied its action. We have seen that:

(1) If we bring near to an insulated and charged conductor another conductor which we have connected to earth, unlike electricity will be "bound" in the latter by influence, and it reacts similarly on the charged conductor. Thus the degree of electrification, and accordingly the free electricity in the latter (*i.e.*, the charged conductor) will be much reduced, and we must again supply it with electricity to raise the free electricity to the original degree of electrification—that is to say, the power of reception or the *capacity* of the charged conductor has considerably increased on account of the proximity of the second earthed conductor. If now the second conductor be removed, then the whole amount of electricity of the charged conductor becomes free and exhibits a much higher degree of

electrification than before. From this cause, therefore, the free electricity has a greater density. By this we are enabled, by means of a continuous supply of electricity of low degree of electrification, to raise a body to a much higher degree of electrification than the source of electricity possesses.

(2) *Volta's plate condenser* enables us to accumulate very weak quantities of electricity, which our electrometer cannot indicate. This is done by repeated charges, which allow us to prove its existence. The Leyden jar, on the other hand, gives us the power of accumulating larger amounts of electricity and of keeping them for a longer time. Also, a large Leyden jar, the outer coating of which is conductively connected to earth, acts as a very constant supply of electricity, which is of advantage in the graduation of the electrometer.

(3) The binding force, and with it the multiplying power of a condenser, is greater the nearer the metallic surfaces are to each other, and the better the dividing stratum insulates. If we take as our unit the multiplying power of an air-insulated condenser, then the ratio of the multiplying power of an insulating plate of equal thickness to the multiplying power of air as insulator, is what is known as the *dielectric constant* of the insulator.

Having learned all the principal phenomena of static electricity which are material for us, we will now turn our attention to those electrical machines which are used to generate larger quantities of electricity.

You will remember that a glass rod, when rubbed with amalgamated leather, becomes strongly charged with positive electricity. By its means we have been

able to perform all our experiments, and even to charge the electric jar, yet with great waste of time. You have now before you (fig. 44) a small *frictional electric machine*, which in a very short time puts forth a much larger amount of electricity than the glass rod and is also much more convenient to use. The place of the rod is taken by a *glass plate* well insulated and capable of becoming strongly charged by friction. The glass plate is made to revolve by a glass spindle resting horizontally on two wooden pillars (T_1 and T_2), is turned by a handle (H), and acts as the thing rubbed. Two amalgamated leather cushions (R) serve as rubbers, being pressed to the two sides of the plate by springs.

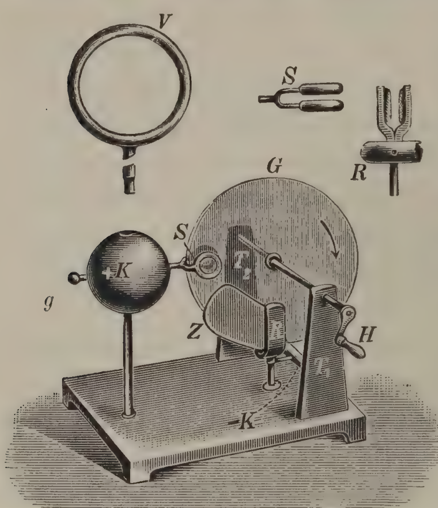


FIG. 44.—Winter's frictional electric machine, $\frac{1}{15}$ natural size.

The *negative conductor* (– K), upon which the – E of the rubber accumulates, is a brass cylinder, connected with the rubber (R), and insulated by a short glass support. The positive prime conductor (+ K) is a well-insulated brass ball, from which projects a brass rod ending in two wooden rings, one on either side of the plate. These bear within a deep groove, but not projecting beyond it, a number of needle-points called the collecting spikes

(S). When the handle is turned in the direction of the arrow, the parts of the plate between the leather cushions are all but touched by the collecting spikes, and the electricity generated is discharged by the action of the points. In this way the positive conductor receives a continuous charge of +E. In order to guard against any loss of electricity, two pieces of silk (Z) are fastened to the rubbers, and the electrical attraction causes them to adhere to the sides of the glass plate.

We shall easily understand the action of the frictional electric machine, when we set it working. I turn the handle in the direction of the arrow. You soon hear the well-known hissing which betrays the flow of electricity. I now approach the knuckle of my finger to the conductor (+K), and a spark of from 4–5 cm. in length shows me that the conductor is charged. By transferring a charge by the proof-ball to the paper electroscope, it is seen to be +E, while the conductor of the rubber naturally yields −E.

I continue turning. The relatively weak output of the apparatus appears to grow less, for the length of the sparks becomes smaller. Now I hook the earth wire to the small conductor of the rubber, and immediately, when the knuckle is approached to the prime conductor, large sparks of from 8 to 10 cm. in length shoot across, causing at the same time a pricking sensation. I can get still longer sparks of from 10 to 12 cm. by fitting on to the large ball a smaller one (g), and putting the knuckle near it. Nor do these sparks decrease when the turning is continued. Whence comes first this uniform and then this increased action of the machine?

Action of the electric machine.

We already know, that by contact a body can only be brought to the degree of electrification of the source whence the electricity is drawn, and that by friction an equal quantity of the opposite kind of electricity is generated. If then the conductor ($-$K), connected with the rubber, has attained the same degree of electrification as the leather cushion, it cannot receive any further $-$E electricity, or in any case only so much as during the turning of the plate is lost by the rubber and the conductor by radiation into the air or by some want of proper insulation. But if the rubber can only take up little $-$E, only a corresponding small amount of $+$E can be free on the glass plate and received by the collecting points of the prime conductor. Hence, too, the positive conductor is only feebly charged. All the rest of the $\pm$E is again united at the moment of its generation. If, however, the rubber is connected to earth, all the $-$E received flows away, and the entire amount of $+$E becomes available.

We thus see that the frictional *electric machine in full action* only supplies $+$E, for the connection of the $+$ conductor with earth to obtain $-$E on the rubber conductor is of no advantage, as this, on account of the rough surface of the leather, holds the electricity less effectually. Its capacity is also much smaller.

There is another means of increasing the action of the apparatus. If I place the intensifying ring (V, fig. 44) upon the prime conductor, the sparks are brighter, but they follow less quickly as the knuckle is drawn further away—the snapping sound grows stronger, but the length of spark not remarkably

greater. We see from this that the ring has increased *not* the degree of electrification, but the capacity, and with it the *quantity of electricity* generated with each single spark.

This intensifying ring consists of a polished wooden ring of a diameter of about 2 cm. Between the two longitudinal sections of the ring, which are glued together, and of the straight piece connecting it with the conductor, there runs a copper wire, with ends bent at the extremity, and so in conductive connection with a brass socket fixed to receive it in the opening of the prime conductor. The mode of action of the ring is not quite clear, wherefore I cannot give you a satisfactory explanation of it.[1]

As we shall soon make the acquaintance of a still more fruitful source of electricity, I shall confine myself to a very few experiments in frictional electricity.

For historical reasons I do not wish to pass over this machine, discovered by Otto von Guericke in the seventeenth century, and constructed in its present form by Winter in the middle of the nineteenth, although to-day it is only of very moderate importance. **Historical.**

I. Instead of the Winter's ring, I place on the prime conductor a wooden rod covered with tinfoil (A, fig. 45), to the upper end of which is fastened a small metal plate which bears many strips of different coloured paper. One turn of the handle of

[1] For example, when the ring is covered with tinfoil, or some equally thick metal coating, the action is weaker; the position of the ring has also some effect, for its action is strongest if its plane is parallel with that of the glass plate.

the machine is enough to make the strips stand up all round (B, fig. 45). Here you have a paper electroscope on an enlarged scale. If I bring the hand near the electrified strips, they will be strongly attracted (C, fig. 45), a process needing no explanation.

II. Perhaps you would yourselves like to play the part of conductor? Let one of you stand on this stool, insulated as you see from the ground by these glass feet, and place one hand gently on the conductor. I turn the handle. Your hair stands on end; still, you feel no other discomfort. Now I put the knuckle of my first finger to your arm. A bright spark appears, showing you are a good conductor, but the smarting pain makes you jump quickly from the footstool.

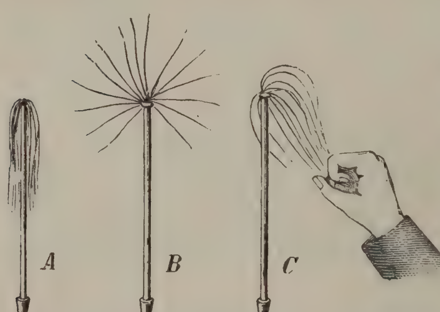


Fig. 45.—Electric paper tassel, $\frac{1}{16}$ natural size.

Divisch's experiment.

III. I set the machine again in motion, and put my left hand near the conductor. Across the short space between, you see sparks flash. All at once they cease. Now try to touch the conductor. Only when quite close there flashes across a small, scarcely visible spark. I change the position of my finger, and immediately you get strong sparks.

The solution of this riddle is easy enough. You see (fig. 46) on the finger of my left hand a wire ring, the bent end of which ends in a very fine point. If I point it towards the charged conductor, the neutraliz-

ing action of the point comes into play. The influence electricity drawn from my body (first kind) streams across through the air (*cf.* p. 41) and unites with the +E of the conductor. The small sparks appearing in the operation are too small to be visible; still, in the dark we should perceive an electric brush discharge.

The Premonstratensian monk Prokop Divisch (a predecessor of Franklin in the discovery of the lightning conductor) almost drove the learned Jesuit

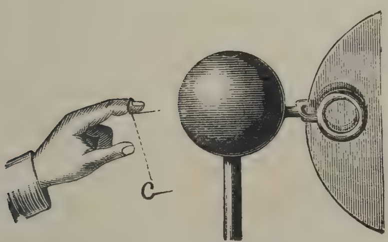


FIG. 46.—Divisch's experiment.

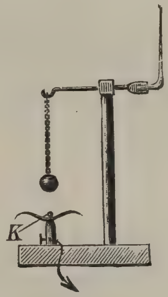


FIG. 47.—Apparatus for the ignition of inflammable liquids, $\frac{1}{10}$ natural size

Franz to despair by this experiment, as he was showing him in 1750 what was, for those times, an electrical machine of very strong action. Father Franz had denied the action of points as stated by Divisch. Divisch, without being seen, brought his needle near the conductor of the machine and stopped its action. The denier of the action of points was conquered!

IV. Here you see a hollow metal saucer (fig. 47), over which swings a small brass ball, hung on a chain. It is connected with an insulated pointed wire. In the saucer, connected to earth, I pour a little

Ignition of inflammable liquids.

sulphuric ether or some other easily inflammable liquid, such as bisulphide of carbon, warmed alcohol or the like, and place the apparatus near the conductor. As soon as I turn the handle, a spark shoots across from the swinging ball to the edge of the little saucer. To oblige it to take its way through the liquid, I place in this last a ball (k) small enough to be quite submerged. Immediately I turn the machine the spark shoots across to the little ball and the ether bursts into flame. After the flame has been extinguished, the experiment may be several times repeated, until all the ether is burnt up. After the saucer has cooled, I place some gunpowder in it. The powder is blown about, without being set on fire.

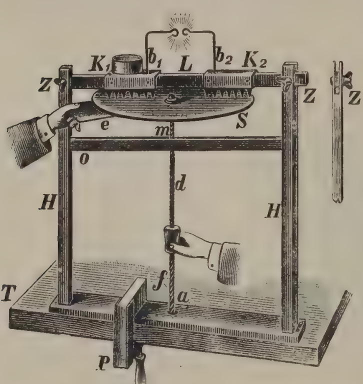


FIG. 48.—Model of an influence machine, by K. W. Dubrowsky, $\frac{1}{11}$ natural size.

As the continual turning of the handle of the electrical machine, on account of the strong friction, is rather tiring, we will perform the further experiments by means of the more effective *influence* electrical machine. In order to understand more clearly the complicated method of action of this highly interesting machine, discovered simultaneously in 1864 by Töpler in Riga and Holtz in Berlin, we will first consider a simple model (fig. 48), constructed by my colleague, Herr K. W. Dubrowsky, in St Petersburg, with the simplest implements. (A very minute description, with exact specification of

Principle of the influence machine.

measurements, will be found in the *Zeitschr. phys. und chem. Unt.*, ix., 1896, pp. 223–225.)

A long drill spindle (A, fig. 48), capable of being turned only in one direction, is fastened into a simple wooden frame in such a manner that its upper end projects about 6 cm. beyond the top, and at this upper end is screwed a thin, round plate of ebonite resting on another small, somewhat stronger ebonite plate, not visible in the figure.

Over it I fix an ebonite ruler (L), bearing two wooden sleeves (k_1, k_2) bronzed over, and spiked on the underside; these all but touch the ebonite plate. Each sleeve has a hole for the insertion of wires (b_1, b_2); and on the left one the cover of a small metal box is fastened, on which a small Leyden jar may be set.

In order that the apparatus may not fall, I clamp it (by P) to the table. Into the holes bored into the side-pieces I put two pieces of wire bent at right angles (b_1, b_2), the looped free ends of which I so adjust that the distance between them is from 2–3 mm.

To set the machine going, I hold an electrified ebonite plate (e) pressed close to the underside of the plate (S), which (by a downward movement of the runner) I put in quick rotation. Immediately you hear a crackling and see a track of sparks flash between the ends of the wire, which lasts as long as I allow the plate to rotate.

This test proves that the conductor, which is opposite (on the left) to the influencing plate (e), is similarly, *i.e.*, negatively electrified, while the other (on the right) is positive. By influence, then, we have obtained from a weak charge of negative elec-

tricity (in e) a much greater quantity of $-E$ and $+E$, without e being discharged.

Let us now pass to the influence machine.[1]

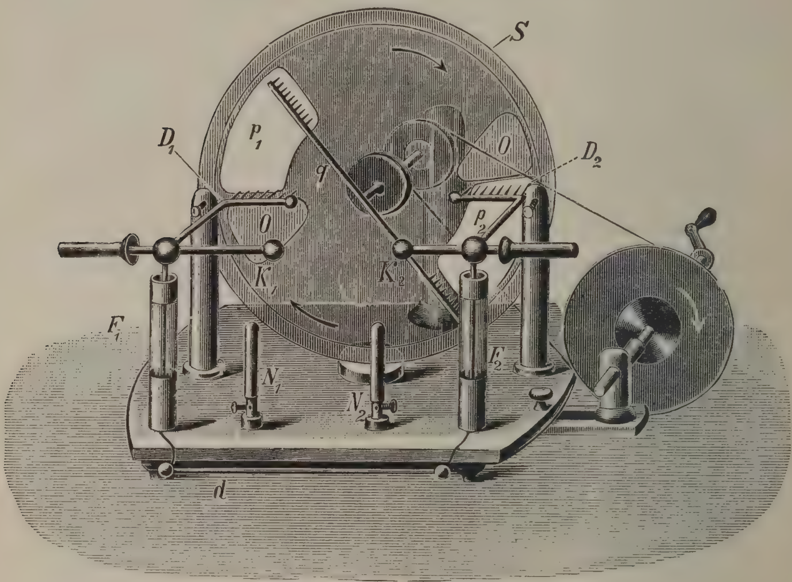


Fig. 49*a*.—Holtz influence machine, $\frac{1}{10}$ natural size.

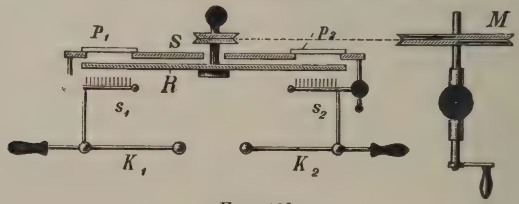


Fig. 49*b*.

Influence machine.

Fig. 49*a* gives you the general view, and fig. 49*b* a horizontal cross-section of the apparatus. You see here two glass plates (S and R), varnished with shellac

[1] In England the Wimshurst machine is found to be more efficient than that of Holtz here described, and has entirely supplanted it. It depends on the same principle, but is self-exciting.—*Ed.*

to increase the insulation; they are placed quite close together. The smaller plate (R) opposite you moves very easily about its horizontal axis, and by means of a belt from the fly-wheel (M) can be made to rotate very quickly. On the back of the fixed plate (S) two pieces of paper (p_1, p_2) are pasted, which serve as exciters. The oval openings (*O*) (windows) are not found in all machines of this kind and are of no importance, as also two pointed pieces of cardboard, fastened to the sectors of paper and sticking through these openings, reaching nearly to the rotating plates and turned towards the direction of their movement. In the specimen before us I have removed them, and the apparatus works at least as well as before.

Opposite one edge of each piece of paper you see in front of the rotating plate (R), and turned to you, two collecting *combs* (s_1, s_2, fig. 49*b*), insulated by strong ebonite supports, connected by strong brass rods to the conductors (K_1 and K_2). These may, by means of the ebonite handles, be pushed nearer to each other or further away. The balls, through which the conductors are passed, are supported by the conducting rods of two Leyden jars (F_1 and F_2), the outer coatings of which are joined by the removable brass bar (*d*).

It would lead us too far afield were I to attempt to explain to you the somewhat involved and not yet universally admitted theory of the influence machine. It will be quite sufficient for our purpose, if, by means of our paper electroscope, I give you a gradual insight into the working of the separate parts.

I touch first of all the two pieces of paper (p_1 and p_2, fig. 49*a*), as also the conductors, with the ball of the electroscope. You see the entire machine is quite

unelectrified. Now I turn the handle with speed sufficient to give about 2 revolutions per second, as we can verify by the help of a pendulum. Let the handle go suddenly—the chalk marks on the black oscillation measure show 52 complete revolutions before it comes to rest. You see thereby, in the case of this apparatus, how small is the friction, and, therefore, the amount of work to be done, in comparison with that required by the frictional electric machine.

Process of charging.

Now I fasten to a support the small insulated proof-ball, which is connected with a paper electroscope by a wire, in such a manner that it touches the sheet of paper p_2 (fig. 49*a*). Then I take away the Leyden jars (F_1 and F_2), and hold the electrophorus cover charged with $+E$,[1] with its under surface close to the sheet of paper p_1, at the same time turning, with the left hand, the handle in the direction indicated by the arrow (fig. 49*a*). Please look at the electroscope. At first you see a slow, then an ever-increasing divergence of the leaves, and very soon they are horizontal. At the same time you hear a gradually increasing hissing, and now begins a rapid shooting over of sparks between the balls of the conductor. The experiment shows that the electroscope, and also the sheet of paper p_2 before unelectrified, has received an increasing charge of $-E$. If I approach my knuckle to the sheet of paper p_1, small crackling sparks shoot across, that is to say, the

[1] In practice the excitement of one of the sheets of paper is caused by placing an electrified ebonite plate on it, but the flint-glass rod or the electrophorus cover has a stronger action. As the ebonite plate has $-E$, then, of course, by charging with it, the opposite kind of electricity is generated in all parts of the machine as before.

originally weak +E charged paper sheet p_1 is also now much more strongly charged than before. The conductors placed opposite to the sheets of paper indicate the same kind of electricity—that is, K_1 has +E, and K_2 −E. While I now turn the handle slowly, I bring near to the surface of the rotating plate an electroscope with its conducting rod ending in a point, after having pushed the conductors together so as not to be disturbed by the sparks. We see that the entire upper half of the rotating plate has −E, while the lower half indicates +E.

The secondary conductor.

You notice on the near side of the apparatus a secondary conductor (q, fig. 49a), placed in front of the rotating plate and fixed, but so loosely that it can be moved, to the ebonite axle of the fixed plate. When the machine is not in action the two collecting combs of the secondary conductor are so placed that one is exactly opposite the upper edge of the sheet of paper p_1, and the other opposite the lower edge of the sheet of paper p_2. While the machine is in full work, I push the secondary conductor just a little over the paper. Immediately the succession of sparks becomes more rapid, the effect of the machine reaches its maximum, and then, if the secondary conductor is pushed still further, it diminishes. What action does this secondary conductor exercise?

I discharge the machine by turning the handle backwards, and to ensure its discharge I run the flame of a spirit lamp over the whole length of the paper sheets.

Now I take away the secondary conductor (q), move the main conductors (K_1 and K_2, figs. 49a and 49b) as far away from each other as before, and endeavour in

the same way as before to put the machine in action. I do not succeed. If, on the other hand, I push the main conductors towards each other until they touch, the machine is excited, and as the main conductors are moved slowly away from each other, a chain of sparks appears, only suddenly to vanish again, if the balls are pushed apart too far. With this—also when the conductors (K_1 and K_2) are pushed together again—the action of the machine stops entirely, though it may again be started; but the conductor K_1 which was before positive, and the paper sheet p_1, now exhibit $-E$, and, *vice versa*, K_2 and p_2 show $+E$. The machine has changed its polarity.

From this it is evident that the secondary conductor (q) exercises some regulating effect upon the action of the machine. But what effect has it, at the beginning of the experiment, *i.e.*, when the apparatus is at rest?

I fasten the cover of the electrophorus by its insulating handle to a support in such a position that it is close to the sheet of paper (p_1, fig. 49a), and I then connect it by a wire with the positive conductor of the frictional electrical machine, the negative conductor being connected to earth. One of you will kindly turn the handle of the frictional machine slowly and regularly, so that I can turn the handle of the influence machine. Look, even though the chief conductors are pushed far away from each other, the influence machine yields a stream of sparks, which becomes the more rapid the more quickly the frictional machine is turned, *i.e.*, the greater the quantity of electricity which is imparted to the paper sheet. But—and this must be noticed—*the influence*

machine working without secondary conductor does not, when acting alone, increase so well and spontaneously the charge of the paper sheets. On the contrary, there is a continual loss of the electricity which is being generated.

We gather from this that: *the function of the secondary conductor is to increase the originally weak charge on the paper sheets and to maintain it at its maximum height.*

We will now try to make the process clear. The main conductors K_1 and K_2 are drawn apart. The paper sheet (p_1, fig. 50) receives at first a small charge of $+E$, and produces by influence through the rotating plate $\pm E$ in the collecting comb s. The $+E$ is repelled and flows into the conductor K_1, while the $-E$ is attracted and, if the other plate is at rest, would entirely neutralize the $+E$ of the paper sheet.

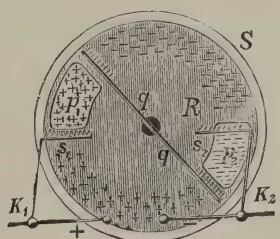


FIG. 50.

As, however, the plate rotates, the $-E$ which has come over to it is expelled before it can unite with the $+E$ of the paper sheet. The upper part of the rotating plate is therefore charged with $-E$.

The plate, now negatively electrified, binds $+E$ upon its far side which is next to the fixed plate, and repels $-E$, but gradually charges the paper sheet p_2. On the near side of the rotating plate, $\pm E$ is again generated in the conductor K_2. The like electricity $-E$ is repelled and flows into the conductor K_2, while $+E$ passes over through the collecting comb s_2 to the rotating plate, and not only discharges it, but also

over-charges it with + E.[1] This action is favoured by the fact that the paper sheet which is being charged with − E also attracts + E, so that soon more + E streams forth from the collecting comb s_2 than is contained in the part of the rotating glass plate just passing by. The lower part is therefore charged with + E. Now the secondary conductor (fig. 50, q) comes into action. Its collecting combs are at first exactly opposite the edge of the paper sheets p_1 and p_2, and are accordingly at a spot where the electricity of the rotating plate is still bound by that of the opposite kind in the paper sheet. On the other hand, in the upper part of the secondary conductor + E is taken from the continually moving negatively electrified part of the rotating machine, and acts by influence upon the rotating plate, the repelled + E of which passes on to the paper sheet p_1, whose + charge is thereby strengthened. That the part of the rotating plate opposite to this collecting comb is charged with bound − E, is no obstacle to the action of points, which, as we have already seen, can act through insulators. In the same way, − E flows from the lower collecting comb on to the paper sheet p_2, by which it is more strongly charged. In the

[1] This phenomenon, according to Professor Arth. von Oettingen, can be shown in the following way: If we take a small ebonite plate and give it a weak charge of electricity by friction, when brought near a charged electroscope it shows − E. If a metallic comb with sharp, fine points is drawn close over the electrified surface several times, the plate shows a weak charge of + E. For this we require a sensitive electroscope; likewise the breadth of the ebonite plate must be less than the length of the comb. The effect is reversed if the ebonite plate is moved to and fro over the flame of a spirit-lamp or gas jet.

secondary conductor also a rapid flow of electricity takes place. If now the machine is charged strongly enough, a strong chain of sparks between the main conductors is emitted. Now the two main conductors assume the part of the secondary conductor, which we may press back a little way from the paper sheet, so that the entire stream passes through the main conductors. The part played by the secondary conductor is now merely to regulate the action of the machine, *i.e.*, to hinder the oppositely electrified parts of the rotating machine from discharging themselves upon the plate itself, by doing which they would much weaken the action of the machine or might even occasion a change of polarity. After what has been said, it is clear that we—if the discharge of sparks in the main conductors by a too great separation of the balls is once interrupted and does not begin again when the conductors are brought near—must replace the secondary conductor in its original position, until the machine is again active.

We have spent a long time on the influence machine. This apparatus is not only interesting on account of its ingenious construction, but it also furnishes us with an instructive application of the law of influence, and offers us a source of electricity as convenient as it is of high tension (in the present machine a maximum of about 60,000 volts) for our further researches.

Whence now comes this quite unlimited supply of electricity, which the influence machine yields under continuous turning of the handle?

Conversion of mechanical energy into electricity.

At first—before the paper sheet became electrified —we gave such a velocity of rotation to the handle that 2 revolutions were made in a second. After

letting go the handle, it made 52 turns before coming to rest. Let us examine this now, when the machine is in full action. You remark the handle makes, after one lets go, only $10\frac{1}{4}$ turns, that is five times less; also we now feel, if we turn the handle again, a much greater resistance than before, *i.e.*, we must now expend much more energy to turn the operating machine. We see from this that electricity is generated by the work required to turn the machine. In this we have an excellent example of the conversion of mechanical energy into electricity.[1]

If I replace the electric jars (F_1 and F_2) and connect their outer coatings with a metal rod (*d*, fig. 49*a*), you see the sparks succeed each other much more slowly, but they are more brilliant and stronger; at the same time you hear, when each spark appears, instead of a hissing a snapping sound. I draw the conductors slowly away from each other. You hear sharp reports and discharges, similar to the lightning-like crackling of a train of sparks.

These artificial sparks grow to 26 cm. in length, as far as I can draw the balls apart. The machine, however, exhibits this strong action only when the atmosphere is quite free from moisture. You perceive, too, a peculiar odour, which becomes the more evident, the better the machine works: this is what is called ozone or "active oxygen." It comes into

[1] This is the classical view of the phenomenon. But, according to the theories of M. Gustave Le Bon, now gradually coming into favour, electricity is but one of the stages which matter passes through on its dissociation and its way back to the ether. In this case we must consider the energy as stored up within the atom on its formation and released on its dissociation. Cf. *L'Évolution de la Matière* passim.—*Ed.*

being from every diatomic molecule of oxygen becoming split up, and forming triatomic molecules of ozone:—

$$O_2 + O_2 + O_2 = O_3 + O_3$$

$$i.e. \quad \underbrace{\begin{matrix} O \\ O \end{matrix} + \begin{matrix} O \\ O \end{matrix} + \begin{matrix} O \\ O \end{matrix}}_{\text{oxygen}} = \underbrace{\begin{matrix} O \\ O \\ O \end{matrix} + \begin{matrix} O \\ O \\ O \end{matrix}}_{\text{ozone}}$$

Ozone represents the more active form of oxygen.

Before showing you, by the help of the influence machine, the action of larger quantities of electricity, I want to put it before you in the dark. Let us pull down the blinds and put out the electric lamp which before illuminated the room. Look, please, at the rotating plate. You see beautiful blue tongues of flame where the $+E$ streams from the collecting combs on to the plate; while, where the $-E$ flows, there only appear small illuminated dots (fig. 51). You have in this a characteristic difference between the two electricities. I again take away the two Leyden jars, and the two balls from the conductor, so that the two blunt points are opposite to each other. If I now set the machine going, we see (fig. 52) at the end of the positive conductor a glowing thread of about 2 cm. in length, which now bursts forth into branches and twigs, forming a beautiful *brush discharge*, as it is called; but on the negative conductor there is only a single spot of light.

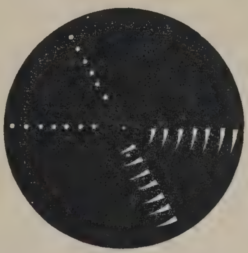


FIG. 51.

In connection with this, in order to show you a characteristic distinction between positive and negative electricity, I fasten to the conducting rod of a paper

electroscope (fig. 53) a horizontal wire, and suspend on the hook at its end a zinc disc (*m*), which I have to-day freshly amalgamated and cleaned. Now I charge the electroscope with + E, ignite a piece of

FIG. 52.—Electric brush discharge, natural size.

magnesium ribbon, and hold it at a distance of about 20 cm. from the zinc plate. No effect follows. Now I charge the electroscope with – E and repeat the experiment. Immediately the leaves fall together, which shows that the negative electricity, under the influence of the magnesium light, is immediately dispelled from the plate into the air, but not the positive. There must then be some relation between the light and this electricity. Recent experiments have shown some actual connection between the phenomena of light and electricity generally, but they are as yet rudimentary, and we are far from the solution of this riddle.[1]

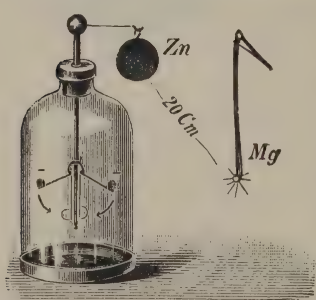


FIG. 53. — Action of magnesium light upon a negative electric body, $\frac{1}{7}$ natural size.

[1] The phenomenon here described seems to be due to the ultraviolet rays. Their effect has been carefully examined by Sir Wm.

We will now perform some experiments with the help of the influence machine.

I. This glass tube (fig. 54), pasted inside or out with a chain of lozenge-shaped bits of tinfoil winding round like the thread of a screw, is fitted at each end with metal caps. If I place this tube on the side arms of the main conductors in such a position that one of the metal caps (*b*) may be in connection with the conductors, and then set the machine in motion, we perceive a very pretty, brilliant serpentine line of light, especially if the two jars are again put in their

Fig. 54.—Franklin's luminous tube, $\frac{1}{8}$ natural size.

Fig. 55.—Black and white revolving disc, $\frac{1}{10}$ natural size.

places and the balls fitted to the conductors. The small sparks flitting about between the pieces of tinfoil give sufficient light to show up plainly every part of the machine. This is Franklin's luminous tube.

II. To make the extremely short duration of the electric spark evident to you, I will illuminate with it a very quickly revolving disc, consisting of sixteen white and sixteen black sections (fig. 55). This I will, by clock-work, cause to revolve so quickly that, Duration of the electric spark.

Ramsay and Dr Spencer in the *Phil. Mag.* for Oct. 1906, *q.v.* According to Dr Le Bon (*L'Évolution de la Matière*, 2[de] ptie., chap. v.), the so-called negative leak occurs from positively as well as from negatively charged bodies. It is doubtful whether it is or is not caused by the emission of an emanation resembling that of radium.—*Ed.*

by day or lamp-light, its colour seems to be a uniform grey.

Let us again darken the room. At every flash of the electric spark the disc seems to be motionless, yet you hear by the humming noise that it is still revolving. It makes about 30 revolutions in a second. At any one point on the disc that we determine, the light and the dark interchange $32 \times 30 = 960$ times a second. During the life of a spark the progress of the plate is so small that it seems to be at a stand-

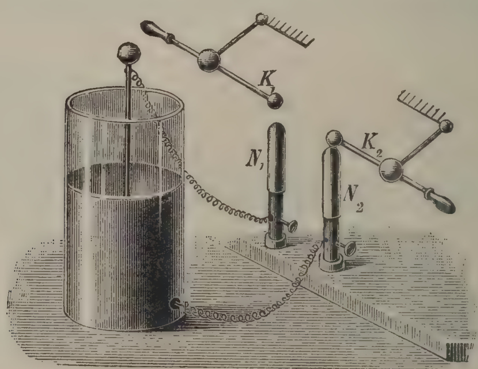


FIG. 56.—Charging a large Leyden jar.

still. More accurate experiments have given us the information that the duration of the discharge of an electric spark is in some cases an infinitesimal fraction, such as $\frac{1}{100,000}$, of a second.

III. Now let us charge the large Leyden jar. I connect both coatings by wires with the hitherto unused secondary conductors (N_1 and N_2), fig. 56, and slide their tops up so that one touches the conductor (K_2) and the other is about $1\frac{1}{2}$ cm. away from K_1. When the machine is turned, sparks are emitted which we can count, so that they give us an approxi-

mate idea of the strength of charge of the jar. After 25 sparks have been counted—and for this very few turns are necessary—I discharge the jar by the discharging tongs. You hear a report as of a pistol shot, and see a short but very bright spark.[1]

Still more remarkable is the action if we take a larger jar, or, what is still more convenient, several Leyden jars, to form what is called an electric battery, by connecting conductively together all the inner and outer coatings respectively of the different jars. In this manner we can increase the capacity of an electric magazine at will. In certain circumstances the discharging spark of an electric battery can pierce glass, melt wire, etc. Conducted to the human body, a battery discharge gives a violent shock which may even cause death.

IV. Here you see two spiral wires fastened on two plates of ebonite or mica, 1 mm. thick, in exactly the same way. At the places where spiral No. I (fig. 57) begins and ends, two wires (such as are used for electric lighting) are connected which end in the metal handles (h_1 and h_2). I place spiral No. I close to spiral II (in fig. 57 withdrawn a little for the sake of clearness), and join the end of wire of No. II with the outer coating of a small Leyden jar and the other end with the discharger (A). If I now put the free end of the discharger to the Leyden jar ball, there springs across to the handle of the other spiral (brought 1–2

[1] By the shocks caused by these sparks, electric waves are set up in the surrounding dielectric (Hertz, 1888). In later times these have been applied to "spark telegraphy" or wireless telegraphy by Popoff in Russia, Marconi in Italy and England, Slaby and Braun in Germany, etc.

mm. nearer) a spark, and a person grasping the handles feels an electric shock. This action of influence is called *electric induction*, and with it we shall have a good deal more to do later.

When strong electrical discharges take place, similar inductive action takes place. If, for example, a spark is drawn from the strongly charged conductor of an electric frictional machine, a person standing near can feel an electric shock, without being directly

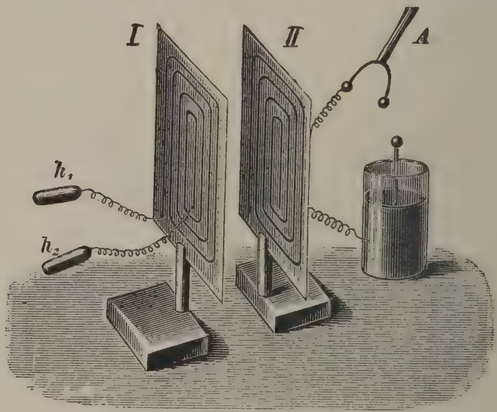


FIG. 57.—Induction spiral, $\frac{1}{15}$ natural size. Distance of plates in experiment, $\frac{1}{2}$–1 cm. Number of spirals, – 10.

struck by the spark. This phenomenon is called the electrical *return shock*. The electric equilibrium of all neighbouring conductors is disturbed by the accumulation of larger quantities of electricity. The opposite kind is attracted and bound. At the moment when the influencing electricity disappears by discharge, the electricity of the neighbouring conductor, hitherto bound, joins with the hitherto repelled and similar electricity. In the conductor there arises in this way, in a certain measure, an electric wave

whose effect in strong discharges may be so powerful, as in the case of lightning, that men and animals may be killed by the electric return shock.

V. We have seen that the work of turning the rotating plate of the influence machine is expended partly in electricity (or more accurately in electric energy), partly in overcoming the friction of the axis and the driving band, and also in heat. We will now try to reverse this process, *i.e.*, by electricity to generate work. Conversion of electricity into work.

I place another machine of similar construction in action, whereby (looking from the front) I charge not the left, but the right side with +E. If I now place both machines with the front of one machine opposite to the front of the other (fig. 58), the like conductors are also opposite each other.

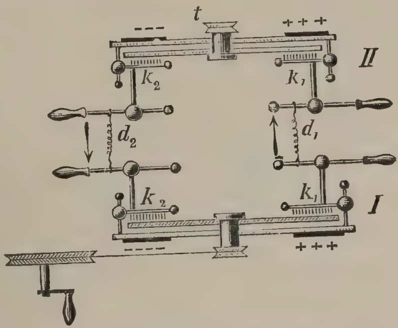


Fig. 58.—Rotation of the plates of a coupled influence machine.

Please notice the direction in which the movable plate of No. II (the new machine) rotates, when I put it in motion. (A little piece of red paper gummed near the axis marks its movement.) Now I connect both similar conductors by two copper wires (d_1 and d_2), and, to lessen friction, I remove the band from the coupled machine II. Now I begin to turn the machine I, and soon a strong hissing is heard, showing the machine to be working well. I give the movable plate of machine II a little push. You see that it begins to rotate quicker and quicker, but the reverse way to what it did before.

I repeat the experiment and purposely push the plate of II in the other direction. It turns round and rotates again, that is to say, in the generation of electricity the plate of the coupled machine rotates in the reverse way to what it did at the beginning.

If I wind a thread carrying a small weight round the driving wheel (*t*, fig. 58) of the II machine, I can, by means of the stream of electricity, raise a weight, that is, convert electricity into mechanical work (Holtz, 1871).[1]

How shall we explain this process?

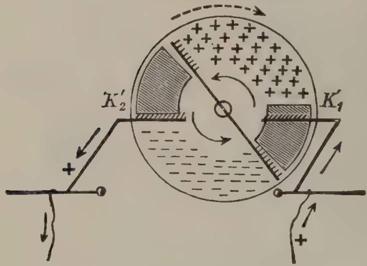


Fig. 59.

Let us consider the rotating plate (fig. 59). The paper sheet to the right has +E, and the movable plate was at first turned in the direction of the hands of a clock; therefore, the lower part of the plate was charged with −E, the upper part with +E. Now +E flows through the collecting comb of the conductor K'_1 (right), and through K'_2 (left) −E. Both collectors attract the unlike electric parts of the movable plate, and repel the like. The movable plate is, therefore, under the influence of two torsional forces, whose effect is joined; hence a slight push is sufficient to

[1] To show this instructive experiment, and explain the conversion of mechanical work into electric energy (p. 111), I employed the old pattern of the Holtz machine, and not one of the new, more convenient, self-exciting influence machines, because with the latter, perhaps on account of the friction of the metal brushes, these experiments are unsuccessful.

cause rotation, which must be in a direction opposite to the former. As in this case the charge of the part continually in motion is strengthened by the electricity added to it, the force of torsion must also increase, and hence the plate must rotate quicker and quicker, until by friction, loss of electricity, etc., a condition of equilibrium is attained, after which the plate continues its rotation as long as the current of electricity does not change.

On account of the generation of electricity, the electrified parts of the rotating plate must have approached the like conductor, and therefore work had to be done against the electric repulsion; immediately the variable parts of electric repulsion (and attraction) have to give way, and in this case, too, work had to be performed. Every electric pendulum, which is drawn from the position of rest by the electrified rod, is an example of this, yet the above instance is very clear.

The electric field.

VI. So far we have examined the condition of electrified bodies themselves. What is the electric state in the neighbourhood of a charged body?

I clear all apparatus away and place one electrical machine on a side table. One conductor I attach to the earth wire; the other to a suspended silk thread. I also fasten a well-insulated wire to the insulated hollow sphere (K, fig. 60, p. 124), standing by itself on the table, or, what is still better, hanging by a silk thread. A lighted wax candle (l) is set in an ebonite stand (*cf.* experiment on p. 127). A platinum or iron wire (p) projects into the flame, and this is bound to a fine copper wire, leading to the conducting rod of an electrometer, the aluminium leaf of which is for this

experiment changed for a red paper one as before. The electrometer stands on a paraffin block, so that the case is also insulated; it may also be connected to earth or to a second candle.

Now one of you will kindly turn the influence machine slowly and regularly. I approach the candle fastened to the electrometer to the electrified ball. You notice a divergence, which becomes continually greater the nearer the candle, the flame of which acts as a number of points (*cf.* p. 59) is brought to the ball K. This is always so, no matter from which side I approach. We thus see that the entire air space surrounding the ball has received a degree of electrification, which varies in proportion to the distance from the electrified body. The entire plane of operation of an electric body we will therefore call the *electric field*.[1]

Now observe the extent of the divergence, while I carry the flame round the ball, keeping as far as

[1] Accurate measurements show that *the degree of electrification of a point in the electric field is in inverse proportion to the distance.* If the ball (K, fig. 60), with a radius r, is charged to the degree V, then a point at the distance $(2r)$ from the centre of the ball will have the degree $\frac{V}{2}$ . . . and one at a distance n times as great the degree $V_n = \frac{V}{n}$.

If then we know the distance of a point from a ball, free all round and the radius and degree of electrification of which is known, we can determine also the degree of electrification of the equipotential surface passing through the point. Similarly, if the radius (r) of the ball, the distance (e), and the degree of electrification (p) of the point in space (here the candle-flame) are known, we can calculate the degree of electrification (V) of the ball $\left(V = p\frac{e}{r}\right)$. This puts us in a position to determine with fair accuracy the potential difference of our influence machine (*see* Appendix, 12, p. 390).

possible at an equal distance from it. The divergence remains constant, *i.e.*, the points in the space, which are equally distant from the ball, have the same degree of electrification. If we had used, instead of the ball, the conical conductor (fig. 14, p. 30), we should have been able to carry the candle round the cone in such a way that the divergence of the electrometer would have remained the same, but the line described by the flame would have been a curiously curved one. This I cannot now discuss, as to do so we should have to overstep the limits of our elementary treatment of electrical phenomena.

The points of the air space, which correspond to a particular degree of electrification, form, with regard to the electrified ball (K), spherical surfaces. Let us imagine these surfaces marked (*a*, *b*, *c*, *d*, fig. 61, p. 125), then they form as it were surfaces of the same electric level; hence they are called equipotential surfaces of the same degree of electrification.

We before saw (p. 50) that an electroscope only indicates really the difference between its own degree of electrification and that of its surroundings (*i.e.*, of its case). We can turn this to an interesting application. I place two lights, such as lighted candles of paraffin or stearine, on the table, and I envelop each one (near the upper end) in a spiral of well-annealed iron wire, the end of which (about 15 cm. long) I bend in the form of a half circle, so that it reaches the flame. To the other end, bent in the form of a loop, I fasten the conducting wire. I connect the conducting wire of one candle with the conducting rod of the paper-leaf electroscope, and that of the other candle with the binding screw of the

case. (In fig. 60 only one connection is given for the former experiment.)

The distance of the candles from the ball is not the same. If the handle of the influence machine is now turned (its negative conductor being connected with the ball K), the electrometer exhibits a certain

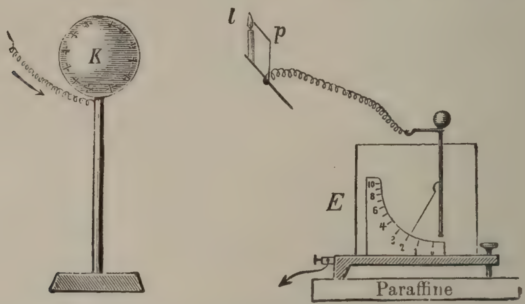


FIG. 60.—Demonstration of electric equipotential, $\frac{1}{10}$ natural size.

divergence. If the candle-flame connected with the electrometer is nearer to the negatively electrified ball than that of the case, the electrometer shows $-E$, but in the other case $+E$. We can now push the candles to such a distance away that the electrometer indicates a certain divergence, say, 1 unit of the scale. We can therefore state :—Between both these electric equipotential surfaces the difference of electric level $=1$: or, they have an electric gradient of 1.

Accurate measurements have shown that equipotential surfaces, which correspond to equal differences of electrification, are the more closely packed the nearer they lie to the electrified body (*a*, *b*, *c*, *d*. fig. 61). These equipotential surfaces have attained lately a great importance for the theory of electric phenomena, and we shall meet them again in atmospheric electricity.

VII. No doubt you know the beautiful magnetic lines which are formed when iron-filings are strewn on a piece of cardboard covering a horseshoe magnet, and a knock is given to it. These are called *lines of magnetic force*, because they indicate the direction in which the forces of attraction between the two poles work.

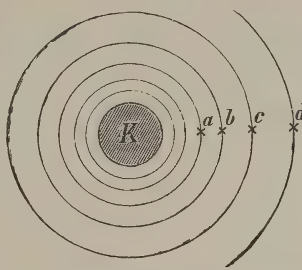


FIG. 61.—Electric equipotential curves.

Now I will show you very similar *electric lines of force*. Into a flat cylindrical glass vessel (*g*, fig. 62) I pour, to a height of about 2 cm., refined oil of turpentine, containing no water, and shake into it a little sulphate of quinine or powdered carbon (*cf.* Appendix, 13, p. 391). Two little wires are fixed at either end, each terminating in a little ball

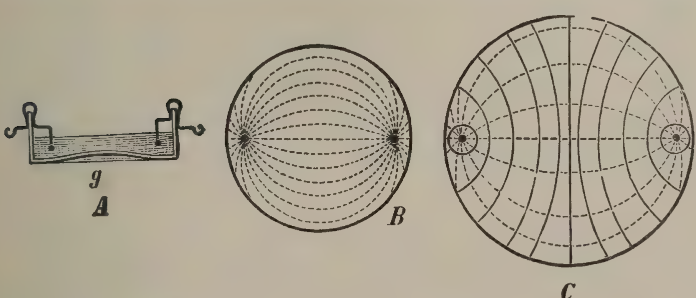


FIG. 62.—A, Apparatus or the excitement of electric lines of force (from an English periodical); B, Electric lines of force; C, Electric lines of force cut at right angles by the equipotential surfaces. A, $\frac{1}{10}$; B, $\frac{1}{3}$ natural size.

dipping into the oil of turpentine, and the other end bent into a hook. I stir up the liquid with a glass stirrer to cause the quinine or carbon powder to distribute itself evenly in the liquid, and place the vessel on

a piece of cardboard, so that the powder in the liquid shows up clearly. Now I connect the two wires with the conductors of the influence machine and begin to turn it *very slowly*. Immediately you see the crystals of quinine group themselves and form beautiful lines (B, fig. 62), which represent the electric lines of force. The form of these lines reminds one of the brush-light of the influence machine (fig. 52, p. 114). Oil of turpentine is a bad conductor of electricity; quinine crystals are half-conductors; the liquid nature of the dielectric surrounding the crystals gives them the power of obeying the forces of electrical attraction. Imagine equipotential surfaces drawn round each of the balls in the fluid (C, fig. 62), and you will find that the electric lines of force always cut the equipotential surfaces at right angles. If I place in the vessel a metal ring, of the same height as the turpentine, you will see little lines of force form in the hollow.

Here I must break off, but must add that the study of magnetic lines of force in recent times is of great practical utility for the construction of powerful electric machines or dynamos.

Accompany me now in thought upon one of the short wanderings I took during my stay in the country during the summer of 1890, in order to study atmospheric electricity. It is 10 A.M., and there is an unclouded sky and little wind.

Our goal is an almost treeless heath, where neither building nor any other raised obstacle breaks the regular course of the equipotential surface of the earth's electricity. An aluminium electrometer serves

as measuring apparatus (E, fig. 63), which differs from that hitherto used by us, by having a circular metal case. The scale is fitted on a mirror forming the back of the case, by which means the accuracy of the readings is increased. The electrometer can be screwed on an ebonite stand, having a brass socket (m_1) at its end, into which fits a wooden staff (H) to be fixed into the ground. A candle in a mica lantern (L) is screwed on to a similar ebonite support, so that when it is fitted on to a wooden staff a metre long, the whole can be raised up to a height of 1–3 metres. Into the flame, as in the former experiment (p. 124), a platinum or iron wire[1] enters, which is connected with the electrometer by a fine copper wire (*Cu*). I hold the candle-lamp at the same height as the metal case, grasp the ebonite handle of the wire, and touch with the end of the wire attached to the lantern the electrometer case, which thus receives the degree of electrification of the equipotential surface in which the flame is now situated. Then I hook the wire to the conducting rod of the electrometer (without touching the case), and lift the lantern 1 metre higher than before. We soon obtain a divergence of 1·5 degrees—or, as 1 division

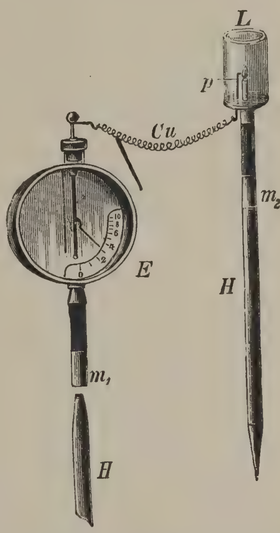


FIG. 63.—Electrometer for atmospheric electricity (E) with flame collector, $\frac{1}{10}$ natural size.

[1] Platinum wire is better, but dearer than the other.

on the scale $=200$ volts—of 300 volts (*cf.* p. 77). If I lower the lantern, the divergence of the leaves decreases and becomes zero when the flame reaches the level of the case. If the flame be now still further lowered, and is nearer the earth than the leaf, the electrometer again indicates a divergence, but $-E$, that is, as if the surface of the earth were charged with $-E$ (*cf.* experiment on p. 124).

I now raise the lantern 1 metre higher than before, *i.e.*, above the level of the case. The divergence $=3{\cdot}6$ degrees of the scale, *i.e.*, 720 volts. At 3 metres difference in height it is 4·8 degrees $=960$ volts. On an average, then, the difference of 1 metre in height gives a difference in the degree of electrification of $(300+\frac{720}{2}+\frac{960}{3})\div 3=326$ volts. A test by means of a piece of sealing-wax shows that in every case the electrometer was charged with $+E$. These numerical values vary according to the place, the day, the season, and the moisture of the air. Still, almost always, when the sky is cloudless, there is a difference of electric level between the stratum of air and the earth, and indeed the higher the collecting flame of the "flame collector"[1] is raised above the surface of the earth, while the case is connected to earth, the greater is the charge received. The value got by us is comparatively small. According to more recent researches (Exner, Weber, etc.), the difference of electric level when the atmosphere is free from moisture, is in general 1300

[1] As collecting apparatus or accumulator, instead of the insulated flame, a jet of water is often used, which streams out of an insulated metal vessel, under equal pressure (water-collector).

volts for every 1 metre in height above the earth's surface. When the sky is clouded the electrometer usually shows $-E$, and during a storm it often exhibits a very variable charge of $+E$ and $-E$.

How shall we explain the rise of a storm, and particularly the huge accumulation of atmospheric electricity, when flashes of lightning 2 to 3 kilometres long are often seen?

According to an idea of Benjamin Franklin in the year 1752, kites were flown, carrying a metal point and connected with an insulated metal sphere by a wire twisted in the flying string. If one limb of a discharger connected to earth were brought near this ball, sparks of 1 metre long were obtained when the kites had mounted nearly as high as the storm-clouds. But by this means the large flashes are not explained.

Rise of storms.

Let us think of the earth surrounded by an insulated envelope of air and swinging in space, as an insulated and strongly negatively electrified sphere; then (not reckoning local elevations) the equipotential surfaces will also form spherical surfaces; and, as a matter of fact, the farther the equipotential surfaces are from the surface of the earth, the smaller is the degree of negative electrification.

Let us again imagine a cloud of moisture, formed by evaporation from the sea (which has the same degree of electrification as the earth), raised to a height of 3000 metres; then, under favourable circumstances or when 1300 volts represent a difference of 1 metre, the difference of electric level between clouds and earth would only be 1300×3000 or 3,900,000 volts.[1]

[1] This example is borrowed partly from Pfaundler (*Lehrbuch d. Physik und Meteorologie*, ninth edition, 1890, iii. pp. 307–308).

Now, according to Warren de la Rue and Müller, a spark 3·4 mm. in length requires a difference in degree of electrification of 13,000 volts. This degree of electrification would therefore give a spark of 3 cm. But more recent researches have shown that in the case of increasing differences in the degree of electrification the corresponding spark lengths are not proportional, but that they increase quicker—however, the length of lightning flashes, which may be several kilometres long, remains a mystery.

In the case of storm-clouds, then, some other circumstance must be at work, and this is probably the condensation of moisture, *i.e.*, the flowing together of particles of moisture to form rain-drops (Humboldt).

According to optical measurements, particles of moisture have a radius of about 0·001 cm. If now a million such particles flow together to form a drop of water of 0·1 cm. radius, and therefore 100 times as great then as we saw (p. 88), the electric capacity of this drop will only be 100 times greater than that of a single particle of moisture. The charge of a moisture-bubble multiplied 1,000,000 times is therefore distributed on a body of only 100 times its capacity, accordingly the degree of electrification must increase $\frac{1,000,000}{100}$ or 10,000 fold. The high degree of electrification of the clouds is therefore generated only immediately before the lightning by condensation of particles of moisture. Still, the gigantic lightning flashes observed in a storm are not yet sufficiently explained.[1]

[1] The electron theory opens new vistas, but the necessary researches have scarcely been set on foot.

The destructive effects of lightning are well known to you. Persons struck by it or by the electric return shock (see p. 118) are either killed or more or less injured. Buildings, trees, etc., are partly burnt, partly demolished; even walls are knocked down. The lightning flashes which do not ignite are called "cold strokes"; yet this name only expresses the occasional action of lightning, for it has been observed that the same lightning which has struck one building as "cold lightning" has set on fire the neighbouring one over which it passed.

The idea of making lightning harmless by means of the action of points (p. 101), by neutralising the electricity of the approaching storm-cloud and conducting the striking flash to earth, is usually attributed to Franklin; but it appears to have been known to ancient civilised races, and at any rate the copper-covered masts and upright obelisks of some of the old Egyptian temples can scarcely be anything else than simple lightning conductors (see Appendix, 14, p. 391).

Franklin's lightning conductor consists of a metal point gilded or covered with platinum, which towers above the building to be protected, its action being at the same time helped by neighbouring points on other parts of the roof. All metal points, as also all greater masses of metal of the building (iron roofs, gutters, gas and water pipes, even if they are inside the building), must, where possible, have their points connected together and with earth by sufficiently strong connecting bars of iron or copper. Especially no faults or weak spots must be present in the earthing, otherwise the first flash of lightning may cause

a fusion by which the conductivity will be interrupted and the entire lightning conductor will form a new danger for the house which it ought to protect.

It must be assumed that the space protected by a lightning conductor is a cone whose point is formed by the point of the conductor, and whose section is a circle, with a radius equal to the height of the cone ($r = h$).

Thus we have made the acquaintance of all the important phenomena of static electricity, and may now attempt—upon the basis of the experience gained—to inquire into the nature of the degree of electrification and form for ourselves an idea of the electrostatic units of measurement.

CHAPTER VI

Hydrostatic and electrostatic phenomena. Meaning of electric capacity. Relation between the electrical capacity of spheres and their radius. Unit of capacity. Relation between quantity of electricity and capacity, as also between degree of electrification and capacity. Proof of these relationships in negative electricity, and by the charging of two bodies with like electricities. Deduction of the meaning of the absolute or electrostatic unit. Practical unit of quantity (the Coulomb). Deduction of the meaning of Potential Unit of electrical potential. Practical unit of this (the Volt). Store of work of an electric conductor.

We have now reached in our wanderings a plain where we can rest awhile, and from a higher point of view cast a glance over the way we have travelled. Not without difficulties has been the path. Often did our goal seem almost within our grasp, when we discovered that the way entered upon was not the right one. The phenomena observed seemed to us, at first sight, so easily intelligible, that we thought we could explain them immediately, only later on to meet with contradictions, which forced us to change our first view and form another, which itself turned out to be only an approximation to the truth. I remind you, for example, of the explanation given of the electrification of an unelectrified body by contact with an electrified one.

When treating of "electroscopic state" or degree of electrification, we gained a knowledge of the Degree of electrification.

mode in which an insulated electrified body acts, when it is conductively connected to an electroscope or electrometer. When graduating the electrometer, we saw that the degree of electrification of a body constantly increased in proportion to the number of charges, as also with the quantity of electricity supplied, and we noticed the same fact with regard to electric *density*. The experiment with the conical conductor (fig. 16, p. 26) proves that electric density depends upon the contour of the surface under consideration; and that, in one and the same body, when the contour varies, the value of this density also varies considerably, and that in the interior of an almost entirely closed conductor it is zero. The *degree of electrification*, on the other hand, is constant both over the whole conductor and in its interior. Hence it follows that the *degree of electrification* is altogether distinct from *density*.

On p. 86 a new notion, that of electric capacity, was brought under our notice. To inquire into the connection of the various conceptions of electrical magnitudes: quantity of electricity, capacity, degree of electrification, and density, and to establish the true standard of measurement of the degree of electrification, will be our present task.

Before giving ourselves to the study of electrical measurements, I will try, by means of a well-known example taken from the domain of hydrostatics, to show you what the real nature of the question is.

You see here (fig. 64) two glass cylinders of the same size, joined together at their bases by a pipe, in

the centre of which is a tap (k) which may be opened or shut, the communication between the two being thereby established or broken at will.

The lower orifices of the two vessels are closed by rubber stoppers, into which glass tubes are inserted, connected by rubber tubing to the middle tube, in which the stop-cock (k) is placed.

Closing the stop-cock, I fill both vessels with coloured water, so that the level in the vessel A is 10 cm. higher than that in the vessel B. The *capacity* of both vessels is equal; the quantity of water (and with it the water level) for the moment *un*-equal. If I now open the stop-cock, water flows from A to B until both vessels have the same level or show the same *degree of fulness* (m, fig. 64). By this operation, the level of the water in A has *fallen* 5 cm., and in B it has *risen* 5 cm.

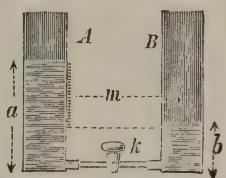


FIG. 64.—Communicating vessels of water.

If the vessel A before had a degree of fulness, and B, b degrees, then after connection both would have the degree of fulness m or $\frac{(a+b)}{2}$.

What would happen, supposing both vessels were of different capacities? I replace the vessel B by a cylinder of twice its internal diameter (*i.e.*, four times greater base surface). Opening the stop-cock, I pour in water, and on both cylinders I paste a centimetre scale, so that the zero-point $(0-0)$ coincides with the water-line (fig. 65, p. 136).

Let us now compare the capacity of the two vessels. With this object I close the stop-cock, and with a dipper pour water into A, until the level has Comparison of capacity.

risen 1 cm. Exactly five dippers full are required,[1] but nearly twenty dippers full, or nearly four times as many, are required to raise the water to the same level in B, that is to say, B has a capacity four times as great[2] as A. When the water reaches the same degree of fulness or water-level, B accordingly contains an amount of water four times as great. Hence we get:

I. *When the degree of fulness of two cylindrical vessels is the same, the amounts of water vary as the capacities.*

Now, opening the exhaust tap (R), fig. 66, I let

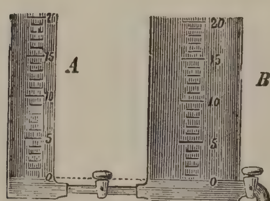


FIG. 65.—$\frac{1}{10}$ natural size.

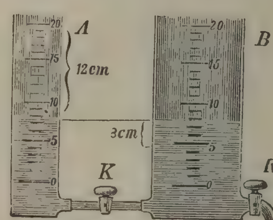


FIG. 66.—$\frac{1}{10}$ natural size.

water flow through k, until the level in both vessels is again opposite zero, and then shut the connecting stop-cock (K). With a dipper just ten times as large as the other one used, I pour into both A and B respectively 10 measures, which correspond, therefore, to 100 measures of the smaller dipper. You see that in A, the level of the water is 20 cm. above

[1] In previous experiments the zinc dipper was cut down to such a point that exactly five dippers full were required to cause a rise of the column of water in A of 1 cm.

[2] It must be distinctly understood that by *capacity* we do NOT mean the maximum amount of water which a vessel can take (that is *volume*), but the *quantity of water* necessary to reach a particular degree of fulness.

zero, and in B only 5 cm. The *degree of fulness* of A and B varies accordingly as 20 : 5 = 4 : 1; but the capacities vary as 1 : 4—that is to say:

II. *When the quantities of water in two cylindrical vessels is the same, the degrees of fulness vary inversely as the capacities of the vessels.*

What happens now if we open the stop-cock (K)? The height of water becomes the same in both vessels, namely, 8 cm. (fig. 66); and at the same time the degree of fulness has decreased 20 − 8 or 12 cm. in A, and increased 8 − 5 or 3 cm. in B. Now as 12 : 3 = 4 : 1, they stand inversely as the capacities. We can therefore say:

III. *If two cylindrical vessels have a different degree of fulness, then after connection they have the same. The differences of degree of fulness in comparison with their former condition vary inversely as the capacities of the vessels.*

I have purposely used the words *degree of fulness* instead of "height of water" to remind you of the similar expression, degree of electrification.

At the beginning we remarked that the vessel B had an inside diameter twice as great as the vessel A, therefore B has a base measure four times as great and—as we found by measurement—a capacity four times as great as A. In cylindrical vessels, then, the capacities vary as their base surfaces. If both cylindrical vessels have a like water-level, then the quantity of water in each vessel is equal to the surface of the bottom multiplied by the height of the water, or, to give it in our own phraseology:

IV. *Quantity of water = capacity × degree of fulness.*

Let us now return to our electrical experiments. We will repeat a few of our earlier ones, using, however, instead of our paper electroscopes, two aluminium electrometers, graduated in the same electric units, and therefore registering the degree of electrification on the same scale. Hence if the two are conductively connected by a wire and then charged (when they must receive the same degree of electrification), they

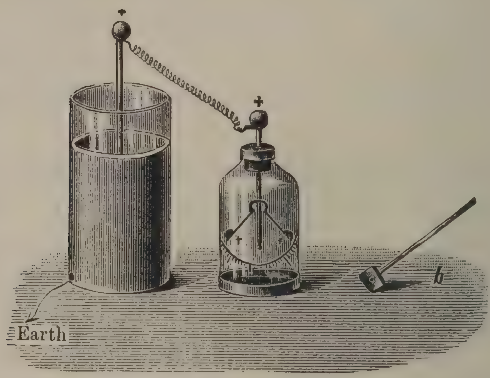


Fig. 67.—Charged Leyden jar as source of electricity. Szymanski and Borgmann, $\frac{1}{12}$ natural size.

will indicate, on the scale, exactly the same degree of divergence.

As source of electricity we shall make use of the large Leyden jar already employed (fig. 67). Its conducting rod is connected to a paper electroscope by means of a thin, uncovered copper wire. The large scale of the electroscope will indicate to us, as the jar is being charged, the increment of free electricity on the inner coating, and enable us to perceive whether, during the experiment we are going to describe, the charge of the jar has remained unchanged.

I now screw upon both electrometers hollow balls, each of a radius = 5 cm.[1]

With a proof-ball or a small block of lead fastened to an ebonite holder (*b*, fig. 67), I touch the ball of the jar charged with +E and transfer the charge of the proof-plane to one of the electrometers by touching the inner wall of the hollow ball. We notice a divergence of 1·3 units. By alternately touching the outer and inner coatings of the jar, I can manage to diminish the charge so that one charge of the proof-plane causes the divergence $a_1 = 1$ unit.[2]

Since, as we remarked recently (p. 89), the capacity of our electric jar is very great, the loss of electricity occasioned by touching it with the lead block is infinitesimal. All the separate charges taken by the plate over a fairly long time may then be considered as exactly equal.

Similar degree of electrification.

To be able to revise our experiments more easily we will number them.

I. What happens if we connect two bodies of the same degree of electrification?

To each ball I give four charges (4L), and connect the two by an insulated wire (*d*, fig. 68). No change

[1] Strictly the balls ought to be insulated and connected to the electrometers by a fine long wire; still, for our experiments, the metal case of the electrometer is a sufficient protection against any disturbing influence action on the leaves.

[2] For this object the earth wire is unhooked and the Leyden jar placed upon an ebonite plate. While the proof-plane is touching it, the outer coating must be connected to earth by touch. The block of lead is chosen instead of the proof-ball, so that, by paring down its edges, the adjustment of the charge may be facilitated.

of divergence follows. I repeat the experiment, giving still larger (and similar) charges to the electrometers. You see the result is always the same, *i.e.*, if two bodies have the same degree of electrification, no electricity passes from one to the other. We can therefore infer that: *Two bodies have the same degree of electrification when, being conductively connected, no electricity passes from one body to the other.*

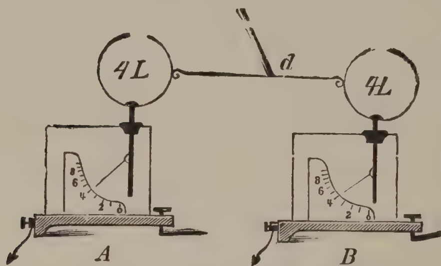


FIG. 68.—Electrometers conductively connected, $\frac{1}{10}$ natural size.

II. What happens in the case when two bodies of *unequal* degrees of electrification are conductively connected?

Suppose I give one electrometer eight charges and the other two (fig. 69). If I connect the hollow balls, the two electrometers show a mean divergence of 5 (in fig. 69 the divergences are indicated by dotted lines). We gather from this that, if two bodies have different degrees of electrification, after being conductively connected they exhibit the same degree of electrification. In this case electricity flows from the body having the higher degree of electrification to the body having the lower degree. The total

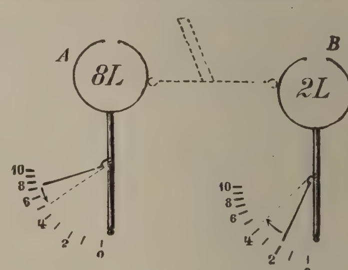


FIG. 69.

amount of electricity is unchanged. Before being conductively connected it was 8L + 2L or 10L; after connection it was 5L + 5L or 10L.

So far we have had bodies of exactly the same form and size, and of equal capacity.

What will happen in the case of bodies of *unequal* capacity?

III. I screw upon the electrometer A a large hollow sphere[1] of 10 cm. radius—that is, twice as great as that on B—and give each ball one charge. The divergence in A is 0·5, but in B it is 1, *i.e.*, the degrees of electrification are in the proportion 0·5 : 1 = 1 : 2. If I give A another charge, making, together with the first, two charges, then A shows the electrical state to be 1, and when A and B are electrically connected no change in the amount of electrification appears (fig. 70).

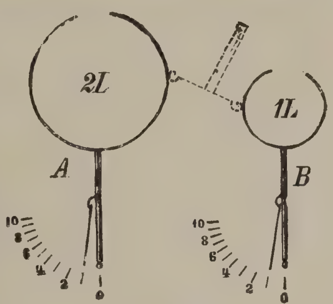


FIG. 70.

Meaning of electric capacity.

If we call the quantity of electricity which is necessary to charge a body up to the first degree of electrification or 1°, *the electric capacity* of the body,[2]

[1] For this experiment we might have taken differently shaped hollow bodies, for instance, cubes of cardboard covered with tinfoil, yet balls have the advantage that they hold electricity better, and also that their capacity is in a simple ratio to their radius, as we shall see immediately.

[2] Recently (pp. 87, 88) by *capacity* we understood that quantity of electricity which would have to be withdrawn from the charged body to *diminish* its degree of electrification by 1 unit; now we mean the quantity of electricity which is necessary to raise the

we see that the necessary quantity of electricity in our balls is $E_a : E_b = 2L : 1L$ or as 2 : 1, and likewise the ratio of the radii of the balls is $r_a : r_b = 10$ cm. : 5 cm. or as 2 : 1—that is:

The electrical capacities of two balls are proportional to their radii.

If, finally, we take as our unit the capacity of a ball of 1 cm. radius, then balls of 2, 3, . . . n cm. radius will have a capacity of 2, 3, . . . n units, *i.e.*,

The capacity of a ball is measured by the length of the radius in centimetres, or, shortly:

$$C = r \quad . \quad . \quad . \quad . \quad . \qquad (1)$$ [1]

According to this, our 5 cm. ball has a capacity $C = 5$, and the 10 cm. ball a capacity $C = 10$.

Now we found that the capacity of our great electric jar, which is our present source of electricity, was 259 greater than that of a ball of 10 cm. radius; then the capacity of the jar is $259 \times 10 = 2590$, that is to say, the capacity of our electric jar is just as great as that of a free ball of 2590 cm. radius, or 51·8 m. diameter, as has been already calculated (p. 89).

How does the degree of electrification of a body depend on its capacity?

degree of electricity 1 unit (more accurately to charge it from 0 to 1). This is in the main the same. It must be remembered, once and for all, that *capacity* does *not* mean the maximum *charge* which a body can receive. The amount of the electric charge receivable by an insulated body depends upon the nature of its surface, on the transient insulation of its supports, and on the condition of the surrounding air—it is therefore undetermined.

[1] More accurately $C = k \times r$ where k is a constant, depending on the chosen unit of electricity and the degree of electrification (*cf.* note 2, p. 159).

IV. We have already seen, that, in order to electrify the large ball with capacity = 10, up to the same degree 1, as the small ball of capacity = 5, a charge twice as great was required (*cf.* fig. 70). I again repeat the experiment. You see that to keep A and B up to the same degree of electrification :

A requires	2	charges,	B, 1	charge	
A	,,	4	,,	B, 2 charges	
A	,,	6	,,	B, 3	,,
		etc.			

Hence we gather finally :

When the degree of electrification of two bodies is the same, the quantities of electricity are proportional to their capacities.

$$E_a : E_b = C_a : C_b \quad . \quad (2)$$

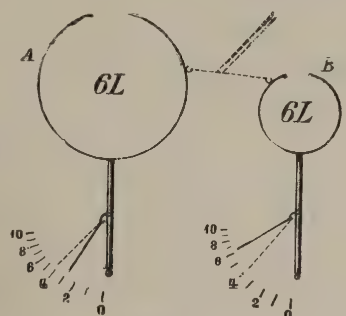


Fig. 71.

If, as in Experiment III, we give to both bodies equal charges, namely 1, then the electrometer connected to the large ball indicates only 0·5, the other 1 ; hence, when the quantities of electricity are the same, the larger ball receives a lower degree of electrification.

Now I give each ball 6 charges (fig. 71). You see, in A the divergence = 3, in B = 6, *i.e.* :

When the quantity of electricity of two bodies is the same, their degrees of electrification vary as their capacities.

$$V_a : V_b = C_b : C_a \quad . \quad . \quad . \quad (3)$$

If now both bodies are connected conductively, then both electrometers exhibit the degree of electrifica-

tion which may be stated as 4 (indicated by dotted lines, fig. 71). In this case the smaller ball B has given 2 charges to the ball A, for its degree of electrification fell from 6 to 4, *i.e.*, 2 units, while the degree of electrification of A—on account of its double capacity—fell from 3 to 4, *i.e.*, only 1 unit. We see, therefore:

Differences of the degree of electrification.

If two balls are placed in conductive connection, they receive the same degree of electrification; in comparison with the former degree of electrification, the differences of the degree of electrification here appearing are inversely proportional to the capacities of the two bodies.

We see that these electrostatic laws so far are in full agreement with the hydrostatic laws observed before. It is only necessary to substitute for "degree of fulness," the expression "degree of electrification," and for "quantity of water," "quantity of electricity," in order to make use of the laws which have been discovered for electrical phenomena. We observed that

Quantity of water = surface × height of water, or
" " = capacity × degree of fulness.

Does this law also hold good in electricity?

In an earlier experiment with regard to the charge of the Leyden jar used as source of electricity, we so arranged that one charge of the proof-ball gave to the 5 cm. ball exactly 1 degree of electrification. But as this last ball has a capacity of 5, then each charge (L) of the proof-ball comprises 5 electrical units, such as those with which the electrometer was graduated. There is now (*cf.* fig. 71).

Ball A.	Ball B.
Capacity $C_a = 10$	$C_b = 5$
Quantity of electricity $E_a = 6L = 30$ units	$E_b = 6L = 30$ units
Degree of electrification $V_a = 3$	$V_b = 6.$

The degree of electrification in A is

$$V_a = 3 = \frac{30}{10} = \frac{E_a}{C_a},$$

and in B

$$V_b = 6 = \frac{30}{5} = \frac{E_b}{C_b},$$

that is to say,

$$\text{Degree of electrification} = \frac{\text{Quant. of elect.}}{\text{Capacity}}; \text{ therefore } V = \frac{E}{C} \quad (4)$$

Hence follows the important ratio :

$$\text{Quantity of elect.} = \text{degree of electrification} \times \text{capacity}$$

or

$$E = V \times C \quad . \quad . \quad . \quad . \quad (5)$$

and conversely

$$\text{Capacity} = \frac{\text{quantity of electricity}}{\text{degree of electrification}}$$

or

$$C = \frac{E}{V} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Since we have no sense for the detection of electricity, we cannot be directly aware of the presence of any quantity of electricity in a charged body, much less any measure of it. We are, therefore, obliged to find some indirect means of information. We must observe the *visible effects* which an electrified body causes—such as the repelling force it exercises upon a small body of known weight charged with like electricity,—and hence draw an inference as to the amount of electricity of the repelling body. Before we enter upon this we will spend a few moments longer over our last experiments.

So far, we have only employed $+E$ to charge the balls connected with the electrometer. It is evident that a corresponding charge of $-E$ with regard to its numerical value will yield the same result, if both balls are charged with similar electricity ($-E$), but in this case we must simply mark the degree of electrification as $-V$.

In our two similarly constructed paper electroscopes we before found (p. 18) that equal quantities of $+E$ and $-E$ neutralise each other ($+E$ and $-E=0$).

I screw once more upon the electroscope the 5 cm. ball, so that the capacities of both balls are equal, and by influence charge one with $+E$ and the other with $-E$, to the same degree of electrification. As the capacities are equal and they have the same degrees of electrification, but of the opposite kind, the absolute quantity of $+E$ must equal the absolute quantity of $-E$: therefore when both balls are placed in conductive connection the degree of electrification will be zero. This is really the case.

If I now give A 10 charges $+E$ with the proof-ball,[1] then the degree of electrification $+Z=10$. By influence I charge B with $-E$, so that the degree of electrification will be $-Z=4$, *i.e.*, 4 charges of $-E$. If I connect the two balls by an insulated wire, the 4 charges of $-E$ will carry off 4 charges of $+E$. There remain accordingly $(10-4)$ or 6 charges of $+E$, which distribute themselves, on account of the equal capacity of the balls, uniformly over the two, and therefore each ball will have 3 charges, and receive the degree of electrification $Z=3$. You see that also happens in fact.

[1] *Cf.* p. 139.

If, therefore, insulated conductors are charged with unlike electricity, after being placed in conductive connection, they exhibit a total charge corresponding to the difference between the charges. Whether the remaining charge is + or − depends naturally upon whether the quantity of +E or −E was greater.

According to the law established to-day, this remainder must distribute itself upon the electrically joined bodies in *proportion to their capacities.*

Hence we infer that all the quantitative ratios found by us, between positive electricity, as to quantity of electricity, degree of electrification, and capacity, apply also to negative and to unlike kinds of electricity. With this we have finished the first part of our present task, and we will now proceed to find a standard of measurement for the unit of electricity.

When graduating the electrometer we were careful always to apply equal quantities of electricity to it, but learnt nothing as to the magnitude of this arbitrary unit, *i.e.*, the unit quantity of electricity. To determine this is now our task. We learnt that the force of electric repulsion between two like—or the force of attraction between two unlike—electric bodies was proportional to the charge, and therefore to the quantity of electricity (p. 55). Accordingly, the force of electric repulsion in the same bodies may serve as measure of the quantity of electricity. If we succeed in measuring the force of repulsion by the known force of attraction of the earth, then we shall have discovered the desired measure.

The force with which a small electrified body, at a fixed distance from another charged with the same quantity of electricity, is repelled, is of course equal to the force necessary to keep the movable body in this position, for only then can equilibrium result. This gives us the power of solving our problem.

You see hanging from two hooks in the ceiling fine silk threads to which a small plate of lead (p), of exactly $\frac{1}{4}$ gramme weight is fastened (A, fig. 72). Another exactly similar lead plate (q) is fixed to an ebonite stand, so that when p is in a position of rest it touches q. With an ebonite rod I push p a little aside and electrify q. If I now allow p to fall slowly back, it touches q and receives the same degree of electrification (on account of having the same capacity), as p, and also the same quantity of electricity. If I gave q two charges before, then p and q have one charge each. According to the law of repulsion of two similarly electrified bodies, p is moved away and so somewhat raised up (B, fig. 72). In this position the pendulum p is under the influence of two forces: the force of electrical repulsion a and the force of gravitation g, which endeavours to pull back the pendulum to its position of rest, that is to say, the component k

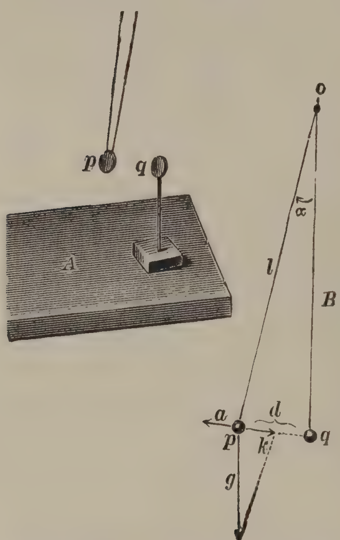


FIG. 72.—Determination of the absolute unit of electrical quantity.

force of gravitation = the component a force of electrical repulsion.[1] Evidently k forms a particular fraction of the whole force of gravitation g, which depends on the length of the thread (l), the angle of divergence (α), and the weight of the pendulum, and may be calculated therefrom (Appendix, 15, p. 392).

We can arrange the length of thread and the weight of the pendulum in such a manner that when the pendulum makes a deviation of 1 cm. (the distance from the centre of the plate), the force which the pendulum (p, fig. 72) exerts in its endeavour to return to its perpendicular position forms a certain fraction of the force which the earth exerts upon a body of 1 gramme in weight, and which is known in mechanics as the "dyne" or unit of force.[2] Dyne.

That quantity of electricity which must now be given to each of the two plates p and q to cause a deviation of 1 cm. from the perpendicular, makes equilibrium by means of the force of electrical repulsion and is therefore called the *absolute unit quantity of electricity*. For a pendulum 1 gramme in weight the length of thread necessary is 9·81 metres or 981 cm., and with it the unit of force "1

[1] It is understood that both electrified bodies are uninfluenced by any neighbouring bodies.

[2] The dyne is the force which, acting upon a mass of 1 gramme for one second, would give it an acceleration of 1 cm. (1 gramme mass = 1 cubic centimetre of water at 4° C.). Since the earth gives to bodies falling freely a velocity g of 9·81 m. (Eng. 32 feet per second) or 981 cm., then the unit of force (1 dyne) = $\frac{1}{981}$ of the strength with which 1 gramme mass is attracted to the earth, or a weight of 1·02 milligrammes at the surface, more accurately stated, in Paris, 45°·50′ Lat. [*Cf.* Lucien Poincaré, *The Evolution of Modern Physics* (Eng. ed.), chap. ii.—*Ed.*]

dyne" will cause a deviation from the perpendicular of 1 cm. If we now give each body p and q such a charge that the deviation is exactly 1 cm., then each body has the *absolute unit quantity of electricity*, also known as *the electrostatic unit.*

Absolute electrostatic unit of quantity of electricity.

The *electrostatic unit is accordingly that charge which exerts upon another charge of the same magnitude at a distance of* 1 *cm. a force of repulsion equal to* 1 *dyne.*

Thus we have found the required unit quantity of electricity. Yet this unit is for many measurements (as those, for example, in galvanic electricity) very inconvenient, on account of its smallness, because by it very high numbers are obtained—for example, with a stick of sealing-wax, several hundred electrostatic units can be got by merely rubbing it gently with fur. In dynamic electricity, which you will study shortly, a practical unit quantity of electricity has been established, called "1 coulomb," in honour of the celebrated physicist Coulomb. This practical unit contains 3000 millions of electrostatic units,

$$1 \text{ coulomb} = 3 \times 10^9 \text{ electrostatic units.}$$

In order to get a clear understanding as to what 1 coulomb represents, imagine each coulomb of like electricity at a distance of 1 kilometre from the next. Then the force of repulsion would be 900 kilogrammes.[1]

[1] According to the law of electrical repulsion, p. 63, the force of repulsion

$$a = \frac{e \times e'}{r^2}. \quad \text{Now } e = e' = 3 \times 10^9;$$

$$1 \text{ kilom.} = 10^5 \text{ cm.}$$

$$1 \text{ kilog.} = 10^3 \times 981 \text{ dynes}$$

$$\therefore a = \frac{(3 \times 10^9)^2}{(10^5)^2 \times 10^3 \times 981} = \frac{90{,}000}{981} = 917 \text{ kg.}$$

We will now endeavour to establish for the degree of electrification, a similar standard of measurement as for the quantity of electricity.

At the beginning of this chapter we made use of the communicating vessels (fig. 73), by which we determined the height of the water-level in centimetres—that is, in lineal measure.

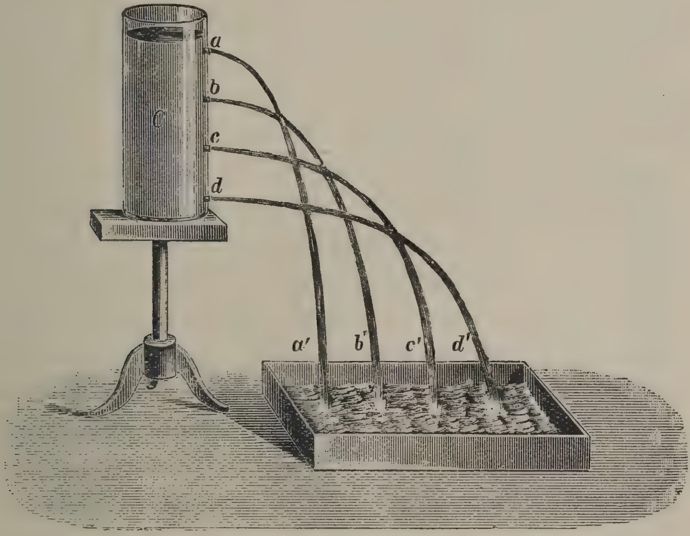


FIG. 73.

But we might have measured the difference of level in another way.

Here you see (fig. 73) a high glass cylinder, with four openings at the side, of exactly equal size (a, b, c, d); the inflow of water can be so regulated by a stop-cock, that the water-level in C always remains constant.

You, of course, understand that the velocity of outflow, therefore also the force of each stream of water,

is greater in proportion to the height of the water above the outflow pipe. The mechanical energy which the water flowing from a, b, c, d, in the same times could expend—indeed each stream immediately on its exit could turn a small mill—will only depend on the height of water, or, as we said, the "degree of fulness," and not on the quantity of water in the vessel C; that is to say, if we take a vessel twice as broad or as small again, but having the positions of the openings a, b, c, d, unchanged with regard to the height of water, then the streams of water a', b', c', d', will still remain unchanged. The work which each of these jets could do is, therefore, a *measure* of the height of water above the openings in question. How great, then, is this work?

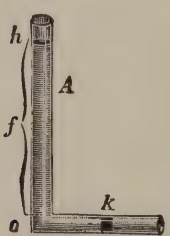


FIG. 74.

Let us imagine that in the outflow pipe of a vessel (A, fig. 74) there is inserted a piston (k), which is able to move in the horizontal tube without friction; then the piston, by pressure of the column of water $oh = f$, will be pushed towards the opening, unless we stop it by means of some counter-pressure. The required counter-pressure in this case must be, of course,—for if the piston is at rest, equilibrium between the two forces must result—equal to the pressure of the column of water $oh = f$, and therefore equal to the height of water (f) × the cross-section of the piston. From this it results that the force we must expend in holding the piston in its place must be in direct proportion to the height of water. If we take away the counter-pressure, the piston will be forced towards the outside, and in

doing this work must have been done. Exactly this same work must we now do against the pressure of the water to push the piston back along the same length.

Let us suppose that the vessel (A, fig. 74), as also the outflow tube and the piston (k), have the same cross-section q or 1 sq. cm. If we now push the piston 1 cm. in the direction of the water-pressure, then 1 cubic centimetre = 1 gramme of water is pushed into the vessel A, and the entire column of water $oh = f$ (which is f cm.) will be raised 1 cm. The water-column f contains f grammes of water. Now, according to the laws of mechanics, the work necessary to raise f grammes 1 cm. high is just as great as the work we must do to raise 1 gramme to the height of f cm. Or, in our case, the work which is required to raise f c.cm. of water in the vessel A 1 cm. is equal to the work necessary to raise 1 c.cm. to the height of the column of water $oh = f$. The resistance which we have to overcome in this instance is the attraction which the earth exercises on 1 c.cm. of water (*i.e.*, on the mass 1). The work necessary to raise 1 c.cm., *i.e.*, the unit quantity of water, against gravitation from the surface of the earth to the water level, we can now make use of as the unit of measurement for the level of the water.

If we take two vessels of water A and B of different degrees of fulness, then we can express the difference of level $(a-b)$ in two ways :—

1. In lineal measure, *e.g.*, in centimetres, or

2. According to the measure of work, *i.e.*, by the work required to raise the unit quantity of water from a lower level to a higher one. This mechanical

Meaning of potential.

measure of work of the difference of level is called the *potential*.

You will ask, and rightly too, why we have taken such a troublesome path to measure the difference of level, when in the *lineal measure* we already possessed a practical and convenient means.

You saw that an insulated, electrified ball K (fig. 61, p. 125) generated in the surrounding air an electric field, the *intensity* (degree of electrification) of which we can determine at particular points with the help of the electrometer. As calculation shows, the degree of electrification of a point in the electric field is in inverse ratio to the distance from the centre of the ball. We were able to convince ourselves by experiment that equipotential surfaces of equal degree of electrification surround the electric body, and that, for like differences in the degree of electrification, the differences of the equipotential surfaces in question became smaller, the nearer we brought the collector to the electrified ball. It is quite clear that it would be impossible to employ a lineal measurement for a case of this sort.

Let us suppose that there is in this electric field a very small insulated ball charged with the unit quantity of electricity of the same sign, then in the various equipotential surfaces it will be repelled with varying force from the ball (K, fig. 61). If we are able to determine the mechanical work necessary to force our proof-ball (with the charge $=1$) against electrical repulsion from one particular equipotential surface to the next higher one (*i.e.*, to one lying nearer the

ball K), in this work we have found a measure for the difference of the electric levels in question.

As the meaning of mechanical work has been accurately defined, with it we also get the required mechanical measure of work for the difference of electric level (electric potential).

Our task is now to establish the kind of work to be done and the unit of work to be chosen.

If we connect each of the hollow spheres A and B (fig. 75) with the inner coating of a large Leyden jar, of which the outer coating is connected to earth, on account of the great capacity of the jar, and the trifling withdrawal of electricity, each of the spheres A and B will keep their degree of electrification unchanged. In this case the degree of electrification A will be greater than that of B.

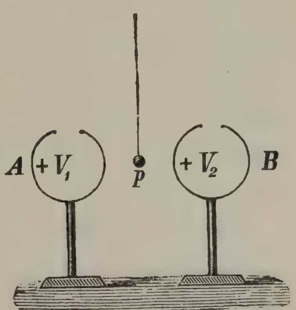


FIG. 75.

If we hang by a silk thread the insulated disc-like pendulum (p), which is charged with the unit quantity of electricity, between both balls, then it will be repelled by both, but on account of the preponderant attraction of A, it will be driven from A to B by the force corresponding to the difference of degree of electrification $V_1 - V_2$. If we allow the pendulum to move from A to B, it will perform a certain amount of work; *vice versa*, in order to move the pendulum, charged with a unit of electricity, from B to A—therefore against electric repulsion—a certain amount of work exactly equal to the former in magnitude must be done. Let us imagine the degree of electrification

of the ball B to be lowered from V_2 to V'_2, then the difference of degree of electrification $V_1 - V'_2$ will be greater than $V_1 - V_2$ was before, that is to say, the force of repulsion of the ball A in comparison with B will be greater, as also the work which we must perform to transfer the unit quantity of electricity from B to A.[1] We see also that the work which is necessary to transfer the unit quantity of electricity from one body of lower degree of electrification to another of higher degree of electrification may also yield a measure for the difference of the degrees of electrification of both bodies, just as before the work required to raise the quantity of water of a lower level to a higher one was that for the difference of water-level. It is therefore only necessary to find the unit of work.

Let us consider the two silk threads by which the disc-pendulum (p) is suspended as very long and fine; then very little work is required to push the pendulum aside. If the pendulum charged with a unit of electricity is moved from B to A against the force of electrical repulsion, then, in this case, the work expended in this has only to overcome the electric force of repulsion in direct proportion to the

[1] We can imagine this transfer to take place in the following way. The disc-pendulum (fig. 75) by contact with the ball B receives a certain charge. If we choose such a small pendulum that it takes up exactly the unit quantity of electricity, then we can bring the disc p to the upper edge of the hollow ball A, and let it drop into the opening (so that the charge of the disc must pass over to the ball A). In this way we have in fact raised the unit quantity of electricity from a low electric level to a higher. It is of course supposed that the two electrified bodies A and B are at such a distance from each other that there is no attraction by mutual influence.

difference of degree of electrification, $V_1 - V_2$. Let us call this difference of degree of electrification, *difference of electric level*, then we can call that work necessary to raise the unit quantity of electricity from a lower electric level to a higher the value of the work of the difference of electric level, and call it the difference of electric potential.

Meaning of difference of electric potential.

The difference of electric potential between two electrified bodies is the work which must be performed to raise the positive unit of electricity from the lower electric level to the higher.

If we place the ball B (fig. 75) in conductive connection with the earth, it receives the degree of electrification of the earth or zero; accordingly the difference of level between A and B now = $V_1 - V_2 = V_1 - 0 = V_1$—that is to say, the whole power of repulsion from A comes into operation. In order now to transfer the unit of electricity from B to A from the level 0 to the level V_1, an amount of work is necessary which is proportional to the degree of electrification of A, and is called the electric potential of the body A.

We can now measure the work to be done in units of work. The meaning of electric potential may therefore be expressed as follows:—

The electric potential of a body is the measure of its degree of electrification expressed in units of work (*cf.* Appendix, 17, p 393).

The electric potential.

What degree of electrification shall we now take as unit of work? Plainly that which demands the unit of work to raise the electrostatic unit quantity of electricity from zero potential (*i.e.*, that of the earth) to that of the body in question.

Work consists in the overcoming of an obstacle, therefore of a force during a movement. Thus work is necessary to raise a burthen against gravitation, to pull a bow or a rubber tube, in which latter case the elastic tension has to be overcome.

The unit of work, the *erg*, is the work by which the unit of force (1 dyne) will be overcome, and the unit of space (1 cm.) covered, or, more simply :

The *erg*.

1 *erg of work will be done if a body is moved* 1 *cm. by the overcoming of* 1 *dyne.*

The unit of potential.

We can now choose the absolute unit of the degree of electrification so that the unit of work (1 erg.) is necessary to transfer one electrostatic unit quantity of electricity from the earth[1] to the body concerned. We then say that the body has its electrostatic potential = 1.

The volt.

This electrostatic unit of potential, on account of its magnitude, is too inconvenient for practical purposes, therefore a practical unit of potential has been devised and called the "volt" in honour of Volta.

The volt is accordingly the practical unit of potential and also the practical measure of the degree of electrification. It corresponds to about $\frac{1}{300}$ of the electrostatic potential unit.

[1] In this case we must not imagine that the proof-body charged with the unit of electricity must be raised from the surface of the earth to that of the body concerned. Consider (B, fig. 75, p. 155) a hollow sphere B connected to earth. Then it has on its entire surface and in its interior the degree of the [electrical] state of the earth, *i.e.*, the level of 0. If we now put the pendulum (p) in the interior of this hollow ball and charge it with a unit of electricity, we only need draw it out and drop it into the interior of the other hollow ball (A) to bring one unit of electricity of the level of 0 to the level of the body (A).

1 volt $= \frac{1}{300}$ of the electrostatic unit of potential.

As the electrometer indicates the degree of electrification of a body connected to it electrically by a long fine wire, we can determine the corresponding potential by observing the degree of electrification. Now our electrometer has been graduated[1] in such a way that when the standard condenser was employed, 1 unit on the scale corresponded to 1 volt. As we know the capacity of this condenser, we can also, by using the electrometer, calculate the value of the potential appertaining to it.

In this sense, therefore, the electrometer also measures the electric potential.

If, then, in the quantitative ratios found by us between quantity of electricity, degree of electrification, and capacity, instead of the expression *degree of electrification*, its measure of work, namely, *potential*, is used, then our laws take the following form :—

(1) The electric capacity of a body is measured by the number of electrostatic units which must be added to it to raise its potential from 0 to 1 electrostatic unit of potential.

In spheres the radius (in centimetres) is a measure of electric capacity ; therefore :

$$c = k \times r. \qquad (1)$$[2]

(2)

$$\text{Electric quantity} = \text{potential} \times \text{capacity}. \qquad (2a)$$

[1] This graduation will be explained later in discussing the method of action of galvanic elements.

[2] An insulated ball of 1 cm. radius requires $\frac{1}{300}$ electrostatic unit to become charged up to 1 volt, therefore k here $= \frac{1}{300}$ (Appendix, 22, p. 397).

or (as we have learnt, p. 159) for practical purposes the volt serves as unit of potential; hence the practical measure of quantity of electricity = volts × capacity.

$$E = V \times C \quad . \quad . \quad . \quad . \quad (2b)$$

From this it follows:

$$\text{Potential} = \frac{\text{quantity of electricity}}{\text{capacity}}\ ;\ V = \frac{E}{C} \quad . \quad (2c)$$

$$\text{Capacity} = \frac{\text{quantity of electricity}}{\text{potential}}\ ;\ C = \frac{E}{V} \quad . \quad (2d)$$

(3) Electric density is that amount of electricity which would appear on the unit of surface of a body (therefore on 1 sq. cm.) if the electricity—of the same density as on the point of the surface concerned—could be spread evenly over 1 sq. cm.

Accordingly on a sphere:

$$\text{Density} = \frac{\text{quantity of electricity}}{\text{surface of sphere}}\ ;\ D = \frac{E}{4\pi r^2} \quad . \quad (3)$$

(4) *The force of electric repulsion* cannot be expressed so easily by a formula. In two very small similarly-electrified balls, at a proportionally great distance (r), the force of electric repulsion (A) is proportional to the amounts of electricity (E_1 and E_2), and inversely proportional to the square of the distance (Coulomb's law). As we already know

$$A = \frac{E_1 \times E_2}{r^2}.$$

On the other hand, the force of electric repulsion which an insulated electrified body exercises on a neighbouring point charged with like electricity, is dependent on the electric density and also on the position of the point [*i.e.*, whether it is quite close to

or on the surface, or in the interior of a hollow space (Appendix, 20, p. 396)] and therefore differs, but the electric potential on the whole conductor and in the interior of the same is constant.

This was also proved by our experiment (fig. 19, p. 37), for if the degree of electrification of the cone was the same all over, so also must its measure of work, the potential, be unchangeable.

In conclusion, we will also endeavour to determine the work which must be done by a charged conductor, if we conduct it to earth. The energy stored up in an electrified body is, of course, equal to the work which we must perform to charge it up to the given potential.

Let us imagine several insulated balls of equal magnitude (r = 300 cm., see note 2, p. 159), and of such capacity that one electrostatic unit quantity of electricity is required to give a charge to each of 1 volt. Let us connect to earth one such ball, the charge of which $=1$, and the potential $=1$ volt. Then the electricity in flowing away must perform a certain *work*. Now 1, 2, 3—n balls will of course perform 1, 2, 3—n times more work than a single ball. Let us connect the n balls (by long wires without capacity), then the degree of electrification, as well as the potential (1 volt), will remain unchanged, but the quantity of electricity is n times greater than in one ball.

From this it follows that the work performed in the discharge—when the potential of the bodies is the same—is in direct ratio to the quantity of electricity concerned. Elsewhere we saw that it

requires 2, 3—*n* times as much work to charge a body to the potential of 2, 3—*n* volts, in comparison with the work required for charging up to 1 volt. *Vice versa*, a certain body, which is charged up to 1, 2, 3—*n* volts, can perform 1, 2, 3—*n* times the amount of work as with a charge of 1 volt.

If, therefore, an electrified body performs with a charge of 1 volt and one quantity of electricity = 1, a certain work which we will call a, then the bodies (*e.g.*, spheres) perform

	with 2 volts	and quantity of	electricity	= 1,	a work	= 2a
or	„ 1 volt	„	„	= 2,	„	= 2a
	„ V „	„	„	= 1,	„	= V × a
	„ V „	„	„	= E,	„	= V × E ×

that is to say, the energy stored up in an electrified body is therefore proportional to the product V × E, that is to say, the potential × the quantity of electricity. *The product of the potential × quantity of electricity is now the required measure for the energy stored up in an electrified body.*[1]

If we take as unit of potential the volt, and as the unit quantity of electricity the coulomb, then the product 1 volt × 1 coulomb (called 1 volt-coulomb) is the practical unit of work which is necessary to charge the body to the determined degree of electrification, or which the quantity of electricity stored up in the body could perform, such as the heating of the

[1] According to Ostwald, every form of energy is composed of an intensity and a quantity factor; or, in this case, of a degree of electrification and a quantity of electricity; or, if we substitute for the former a unit of work, of a potential and a quantity of electricity.

conducting wire or the chemical decomposition of a fluid conductor (Part II.).

Now we saw (p. 159)

$$1 \text{ volt} = \tfrac{1}{300} \text{ electrostatic potential units}$$
$$1 \text{ coulomb} = 3 \times 10^9 \text{ electrostatic units of electrical quantity,}$$

and as

$$1 \text{ volt} \times 1 \text{ coulomb} = \tfrac{1}{300} \times (3 \times 10^9) = 10^7 \text{ e.-s. units of work (ergs).}$$
$$\therefore 1 \text{ volt} \times 1 \text{ coulomb} = 10 \text{ million ergs.}$$

The practical unit of work, the kilogrammetre, is $1000 \times 100 \times 981 = 98{,}100{,}000$, or, in round numbers, 100 million ergs,

$$\therefore 1 \text{ volt} \times 1 \text{ coulomb} = \frac{10 \text{ million}}{100 \text{ million}} \text{ kilogrammetres,}$$

or, in round numbers,

$$1 \text{ volt-coulomb} = \tfrac{1}{10} \text{ kilogrammetres.}$$

We must from this confine ourselves to pointing out that the volt-coulomb can serve as a measure of electrical work, as it is its direct proportional.

More accurate researches, which we cannot go into here, show us that the amount of work that an electrified body has stored up within it is only equal to half the product of its potential × its quantity of electricity; *i.e.*,

$$\text{store of work } A = \tfrac{1}{2} V \times E.$$

Let us now call to mind that our influence machine, with a length of spark of 20 cm., gained a difference of potential of even more than 50,000 volts. Let us also compare with this the mighty flashes of lightning, sometimes several kilometres long, flashing down from the storm-clouds, so that all artificially generated sparks appear puny in comparison. Its power of

destruction no longer seems to us unintelligible, but forces us to recognise the almighty character of the forces of nature, and to acknowledge that we are very far from being able to bend them to our will.

With this confession of our human weakness we will close this portion of our work.

PART II

DYNAMIC ELECTRICITY

CHAPTER I

The most important phenomena of magnetism. Comparison between magnetic and electrostatic phenomena. The influence machine as source of electricity. The progress of the degree of electrification along a half-conductor connected to one of the poles of the machine. Analogy between hydrodynamic and electrodynamic phenomena. Meaning of electromotive force. Fall of potential in a circuit. Dependence of the fall of potential upon the length of the current conductor. Source of the electric current. Dependence of the fall of potential upon the conductivity of the current conductor.

In static or frictional electricity you have gained some knowledge of a series of phenomena which evince such a striking agreement with the magnetic phenomena now about to be studied, that we are forced to conclude that there must be some hidden bond between the two domains. On closer observation, however, very profound differences will become evident. It will, therefore, be advantageous to compare the most important phenomena occurring in the two divisions. Since the principal qualities of magnets are already known to you, we may confine ourselves only to what is necessary for the purpose in view.

Here is a lump of magnetic iron ore, which consists of a chemical combination of iron and oxygen (Fe_3O_4). The two opposite sides have been polished and are smooth and even. Taking hold of the lump by the

middle, I push it into a small heap of iron filings, and upon withdrawing it you see that particles of the filings adhere to it, but not uniformly. The ends have the appearance of a thick bush, the extremities of which are specially prominent, while in the middle of the mass there is a perfectly free zone to which no particles cling; this part is called the *zone of indifference* (marked *ii.* in A, fig. 76). Those parts, where the magnetic attraction is strongest, we call the *polar surfaces* or poles (*pp*). If now, having scraped off the filings, I present one of the polar surfaces to

FIG. 76.—Magnetic attraction, $\frac{1}{10}$ natural size.

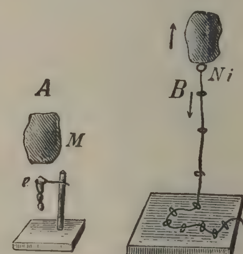


FIG. 77.—A, magnetic influence; B, the different force of attraction of the magnet for iron and nickel.

a piece of iron, this last will be powerfully attracted, and in its turn will acquire the same property as the magnetic ore (B, fig. 76).

Pieces of iron may be attached to both poles so as to form a chain, and it will be found that the different links of the chain exhibit reciprocal attraction, and if any two are brought near each other they adhere together as in B, fig. 76.

This force is also displayed too in the neighbourhood of the poles. If, for example, I place a piece of soft iron in the ring of this retort stand (A, fig. 77) and hold the pole of the magnet just above it, another

piece of iron may be suspended from it; then a second may be added to the latter, which in turn will support a third, and so on; but as soon as I remove the magnet, the whole series falls on the table, just as would happen if, in the former experiment, I were to take hold of the top piece of iron, and at the same time to take away the magnet.

This phenomenon, resulting from the approach of a magnet, is called *magnetic influence*. We shall return to it later.

The force of magnetic attraction is especially manifest in the case of iron; but in some metals, such as cobalt and nickel, it is weak, and in other bodies it is only apparent when very powerful magnets are used. To show you the difference between iron and nickel, I will take pieces of each of almost equal size, finely polished and provided with hooks, from which I suspend, by silk threads, small leaden balls of equal weight, fastened at the same distance from each other on silk threads (B, fig. 77). If I touch the iron with the pole of a magnet, I am able to raise up a string of more than ten of these weights, whereas the nickel ball falls to the ground as soon as the fourth weight is added.

We have seen that soft iron, when brought into contact with or even into the neighbourhood of a magnet, itself becomes magnetized, but loses this quality immediately the magnet is removed. Even repeated stroking with the magnet makes no alteration; but a *steel* rod under the same circumstances becomes permanently magnetized. This gives us the means of providing ourselves with artificial magnets of convenient shape.

This knitting needle is a very good object for our

experiment. I break it in half, and so get two small handy steel rods, which I proceed to magnetize in the following way. Holding one half firmly by the middle, I lay it close to one of the poles of the magnet and draw it along it, being careful that the end of the needle leaves the edge of the pole surface last. While doing this I turn the needle round a little after each "draw." This process I repeat twenty or thirty times. I do the same with the other half of the needle, but with the opposite polar surface of the natural magnet. Now both needles are magnetized strongly enough to hold up pieces of iron heavier than the magnetized needle itself. We can, by means of these magnetic needles, study the peculiar properties of magnets.

From stands, about two inches apart, are suspended by fine twisted silk threads two small stirrups of aluminium wire, and in these I place the magnetic needles in a horizontal position. You see they swing to and fro once or twice and then come to rest parallel to each other. By any compass needle you will see that one end of each needle points exactly to the north.[1]

To distinguish the ends of the needles from each other, we will fix on the *north-seeking* pole of each, which we shall call shortly the "north pole," a ball of sunflower pith coloured red, and on the other end a green one of the same material. Now the ends with

[1] The horizontal deviation of the magnetic needle from the astronomical meridian was, in St Petersburg in 1895, about ½ minute, now almost 1 minute west. For our purposes it may therefore be neglected. This "declination" of the magnetic needle is much greater for places situated further east or west.

the red balls of both needles point north. Hence the red ball marks the north pole, and the green one the south pole of each needle.

The question now forces itself upon us: How does a movable magnet of this kind behave at the approach of a piece of iron or another magnet? I bring an iron key near one of the magnetic needles—one pole is attracted, as is also the other one: that is to say, both poles of the magnet are attracted by the non-magnetized iron, as formerly the iron was attracted by both poles of the magnet.

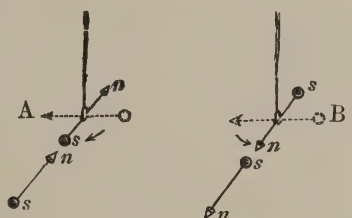


FIG. 78.—Magnetic attraction and repulsion, $\frac{1}{10}$ natural size.

Now I take one of the magnetic needles from the stirrup and, from a lateral direction, advance its north pole towards the movable needle. The latter turns quickly round, swings with gradually decreasing movements to and fro, and then comes to rest in such a position that its south pole is opposite the north pole of the needle which has been brought near to it (A, fig. 78). Scarcely have I turned away the needle held in my hand, when the movable needle swings round and turns its north pole to the south pole of the one presented to it (B, fig. 78).

When the suspended needle has regained its position of rest, pointing north and south, I offer quickly to its south pole the south pole of the other magnetic needle. A strong repulsion is manifested. The same thing happens between the two north poles. Hence we see that: *opposite magnetic poles attract; like ones repel each other.*

Is it possible to separate the poles? I break one of the magnetic needles in the middle and present the portion of the north end carrying the red ball to the suspended needle. We see that a new south pole has been formed. We find also a north pole on the other broken part: that is to say, every broken part forms a complete magnet. I again break the pieces, until the needle is divided into eight nearly equal parts. I place these in a thin glass tube, so that each south pole is followed by a north pole and so on, and then I suspend the glass tube in the empty stirrup: you see that the eight little magnets act as one complete magnet.

Molecular magnets.

If, in imagination, we continue this division of the magnetic needle, there can be nothing against our acceptance of the hypothesis that every molecule[1] of the steel composing the needle possesses a north and a south pole, and therefore that the magnet is composed of very minute molecular magnets, all pointing in the same direction (Weber).

What will happen if these molecular magnets do not point in the same direction, but take up all kinds of different positions? Here we have a test tube of very thin glass loosely filled with steel filings and corked up. By holding it for a long time over the poles of a strong magnet, it is possible to magnetize the mass, consisting of thousands of little pieces of steel, so that the ends of the tube have the power of lifting small bits of iron. Now I loosen the cork a little and shake the tube so much that the filings

[1] By molecules we understand the smallest homogeneous particles of which a body is composed. The indivisible ultimate parts of the molecules are termed atoms. *Cf.* p. 55, *supra*.

are all jumbled up. You see that the magnetism has almost entirely vanished.

From the above we may infer that an un-magnetized piece of steel or iron consists of molecular magnets occupying all kinds of positions with regard to one another. To magnetize is, therefore, merely to set some of the molecular magnets parallel to each other and pointing in the same direction.

The final state of magnetization would be reached when all the molecular magnets were thus arranged; but this cannot be done. The susceptibility of iron to a transient state of magnetization may be a result of the quality possessed by its molecules of turning easily, while the steel molecules combined with carbon are probably less mobile. On the other hand, when these last are once arranged in the same direction, they retain their position. The fact that a piece of steel becomes magnetized more quickly when it is jarred during the process of magnetization and that a steel magnet loses some of its magnetism by a blow or fall, is an argument for our hypothesis.

We have still to decide the question: What polarity does the end of the steel needle receive when stroked with the pole of the magnet? This piece of knitting needle is still unmagnetized. I take hold of it near the end, and draw it along the north pole of a magnet so that the free end leaves the pole last. A trial shows that this end has become a *south pole*. Similarly, if a needle is drawn along the south pole, the part of the needle last touched by the magnet becomes a north pole. For this, direct contact is not even necessary, for the magnetization is successful, although

weaker, when performed by a magnetic pole covered with a thin plate of mica. Even a hard un-annealed iron nail, one end of which I present to a magnetic pole, exhibits after a time some permanent magnetism, and it will be found that the nearer end of the nail has received the opposite, and the further one the same magnetism as the magnetizer. We call this phenomenon *magnetic influence* (p. 169), and we may state that: *magnetizing by stroking or by the approach of a magnet is magnetizing by influence.*

Magnetization by influence.

Now we will try to "discharge" (demagnetize) the magnet by bringing it into contact with various bodies. . . . We do not succeed. Magnetism is therefore not capable of being "conducted." Yet a magnet is almost entirely demagnetized by being heated in a flame.

Let us now summarize the most important magnetic phenomena and compare them with the phenomena of static electricity already familiar to you (*cf.* p. 6).

Summary of the Fundamental Phenomena of Magnetism and Static Electricity

(1) Like magnetic poles repel; unlike attract each other.

Like electrified bodies repel; unlike attract each other.

(2) Any number of steel rods may be magnetized by being stroked by a magnet, and yet the influencing magnet loses none of its strength. Similarly any quantity of +E and −E may be generated without the influencing body losing any of its charge.

(3) A suspended magnet, free to move, assumes in

the magnetic field (also in that of the earth) a certain direction; so, too, does an electrified needle (fig. 6, p. 14) in the electric field of an electrified body.

Phenomena opposed to these analogies are:

(4) If a magnetic needle is broken up into innumerable pieces, every single piece forms a complete magnet (molecular magnet).

(5) Magnetism cannot be withdrawn from a magnet by contact.

(6) A few substances only, such as iron, nickel, cobalt, and their compounds, can be magnetized to any great extent, or can affect the magnetic needle. On the other hand, all sufficiently insulated bodies are capable of being electrified.

From this summary you see that although, in many respects, the similarity between the magnetic and electrostatic phenomena is so great, yet in many others there are very conspicuous differences. This is especially evident in the *binding power* of magnetism, *i.e.* in the impossibility of a body parting with any of its magnetism by communication; or, to put it more correctly, of magnetizing another body at its own expense, or of *discharging* a magnet by contact. Further, the magnetism usually studied is confined to a few bodies (Appendix, 23, p. 397). Electricity, on the other hand, is—at least in conductors—movable, and may be generated in every properly insulated body, whether solid or fluid, by contact or communication. Is it possible to refer these phenomena, showing such divergences of character, to some common cause? That this can be done, we shall see later on.

We have now shortly reviewed those magnetic

phenomena which are indispensable for the understanding of what is to follow, and we will now return to the consideration of matters dealing with electricity.

In the first part of this book we gained a knowledge of the phenomena of static electricity: that is to say, of electricity in equilibrium or a state of rest. This name is much used, but only to mark its general character, because what is known as electricity "at rest" may be conducted and, to speak figuratively, may flow through a wire into another body or to the earth; thus, to a certain extent, *it moves.* We have taken much advantage of this power of movement possessed by static electricity, but the final result has always been the same, that is, a condition of equilibrium has been established. Now we shall give our attention chiefly to the process of electrical discharge in conductors and, therefore, to the so-called "current electricity," which, in contra-distinction to static, is called *dynamic electricity.*

In order to follow the phenomena of current electricity, we must have at our disposal a prolific means of supply. The influence machine, already so much used, may for the present show us upon what the question turns.

I set the machine in action and hook on to the conductors (A, fig. 79), by the hooks attached, both ends of a smooth, thick hempen cord 210 cm. long. This cord, which is a semi-conductor, I fasten to the hook at the end of a taut silk thread (*s*) hanging down from the ceiling. Thus a closed circuit is formed when the machine is in motion.

The simple proof electroscope (B, fig. 79), with paper leaves, hung from wire stirrups, I fasten to an

ebonite rod, and place its lower end, conveniently bent, on the string near the positive conductor.[1]

Will one of you kindly turn the handle of the electrical machine as regularly as possible, so that I may be able to run the electroscope along the string? —We notice that the leaves in the position *a* (A, fig. 79) diverge very much, and that when we put the testing electroscope to the knob of another one charged with vitreous electricity, and standing on the

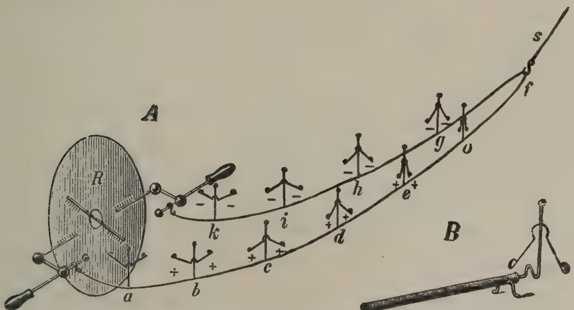


FIG. 79.—A, course of potential in conductor, $\frac{1}{20}$ natural size; B, proof electroscope, $\frac{1}{10}$ natural size.

table near, we find it indicates positive electricity, as was to be expected.

Now I gradually move the hand electroscope along the cord, testing at each interval the nature of the charge. You notice that it is still positive, but it gradually decreases up to the point *o* (A, fig. 79), where the leaves fall completely together, and the cord thus exhibits a zero degree of electrification. If the proof electroscope is pushed further on, the leaves again begin to diverge, but the charge is negative, and increases constantly the nearer the electroscope

[1] Our paper electroscope may also be used, by touching the string with the conducting rod just underneath the ball.

gets to the negative conductor ($f-k$, A, fig. 79). We conclude from this that the degree of electrification, or *the difference of potential*[1] from the zero-potential of earth, decreases (according to the absolute magnitude) continuously in the path of the current from both poles, up to the point marked *o*. At *o* the degree of electrification is zero. Now comes the interesting question: What goes on in (or on) the conductor, while, speaking figuratively, the electricity is flowing through it? What flows, or does anything flow? According to the two-fluid theory, both kinds of electric fluids are generated at the poles of the machine and flow against each other in the conductor. In that case, then, when these opposite electricities meet, they must neutralize each other. How, then, can the steady decline of the degree of electrification until the point *o* is reached be explained? Perhaps both electricities flow past each other, and on the way gradually perform the neutralization. This contradicts entirely the observations hitherto made.

You will admit that the two-fluid hypothesis cannot explain the inner processes of the so-called current electricity. Force of habit constrains us to retain the borrowed expressions "current electricity" (or, in short, electric current), as also $+$E and $-$E, for the want of a more suitable term, just as we speak of the setting and rising of the sun, although Copernicus long ago corrected this error.

[1] The electric potential difference of two bodies is measured by the mechanical work necessary to raise the positive unit quantity of electrostatic electricity from the lower electric level to the higher. The value of the work of the difference of electric potential of a body from the earth is, therefore, the mechanical measure of its degree of electrification.

How does the process fit in with the one-fluid theory? Let me, in order to put it in a clearer light, give you an example taken from hydraulics, as this bears an analogy to the electro-dynamic phenomena we are examining.

Let us imagine a horizontal canal of circular shape (A, fig. 80), filled with water to half the height of its walls. At the point M a dam is made close to the bottom, and in it a turbine or water-wheel works, which can be set in motion by a machine.

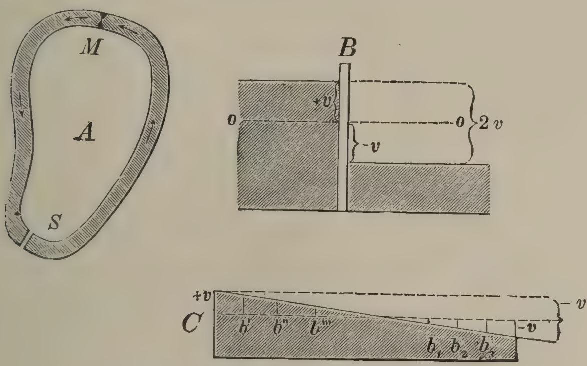


FIG. 80.—Hydrodynamic phenomena.

At another point (S) there is a penstock or sluice, which, for the present, we will consider closed.

What will happen when the water-wheel is working? Naturally the water in the canal will be driven forward (*i.e.* in the direction of the arrow, to the left of M), and will flow into the left half of the canal and there be dammed up, whilst in the other half the water level must fall. At the sluice a difference of level will occur (B, fig. 80), the height or extent of which depends upon the force driving the water, or, as it may be called, the aquamotive force of the machine. This difference of level will go on increasing until

the counter-pressure of the water upon the paddles establishes a condition of equilibrium. From that moment the further work of the machine only serves to maintain the difference of level. The difference of level at the closed sluice may therefore be taken as a measure of the aquamotive force of the machine. As we may term the difference of level, measured by the value of the mechanical work done, potential difference, we may say : *the potential difference at the ends of the canal is a measure of the aquamotive force.* If (according to mechanical measure) the increase of water level upon one side of the sluice $= + v$ (*cf.* B, fig. 80), and the corresponding decrease on the other side $= - v$, then the entire surface or potential difference $= + v - (- v) = 2 v$, as can be seen from B, fig. 80.

While the machine continues working uniformly, let us imagine the sluice-gates opened, so that the canal forms one continuous circular current. The difference of level will try to equalize itself; but as the working of the machine prevents this, a difference of level which depends on the resistance of the current, and generally is much less than before, is maintained. In the canal a condition of equilibrium will soon prevail, because just as much water flows to any particular point as flows away from that point. The fall of level or fall of the current must be uniform in any one cross section of the canal. C, fig. 80, shows a section perpendicular to the axis of the canal; $o - o$ (B, fig. 80) is the original level of the water in a position of rest or zero potential.

Two results follow from the above :—

(1) Let us imagine a pond dug in the space

enclosed by the canal, the surface of which is the same height as the original level of the canal. Let us compare the height of water in this or the degree of fulness of the canal with that of the pond. The degree of fulness in the left half is greater than that of the pond, whilst that in the right half is less. The difference of level of the two, beginning from the left of the wheel, steadily decreases, and at one point will become zero, and then passes into a continually increasing negative difference. Compared with zero level, we have, figuratively speaking, in the left half of the canal *plus* water, in the right *minus* water, or a *positive* and a *negative degree of fulness.*

(2) Between every two points of the stream equally distant from each other (b_1 b_2 or b' b'' C, fig. 80) there is an equal fall of the current or an equal difference of degree of fulness: that is, the fall of the current is constant. Every point of the circular current, compared with points taken higher up the stream, has a lower level and therefore a negative degree of fulness, and, *vice versa*, a positive degree in comparison with points lying further down the stream.

Let us now return to our electrical phenomena. We have already become acquainted with the analogy to the first result (fig. 79) taken from hydrodynamics, in the fact that the degree of electrification, or the corresponding electric potential in the conductor continuously decreased, became zero, and finally passed into an increasing negative value.

We will now consider the fall of the current between two points in the circuit.

I place the paper electrometer (E, fig. 81) with its metal case upon a block of paraffin or with its feet resting on three ebonite discs. In all experiments with the electrometer a much enlarged image of the scale and leaf should be thrown on the screen (*cf.* fig. 16). To the ebonite rod (l) two movable brass binding screws are fixed, to which two thick German silver rods with hooked ends (m_1 m_2) are soldered. To the screws I fasten two very fine bare

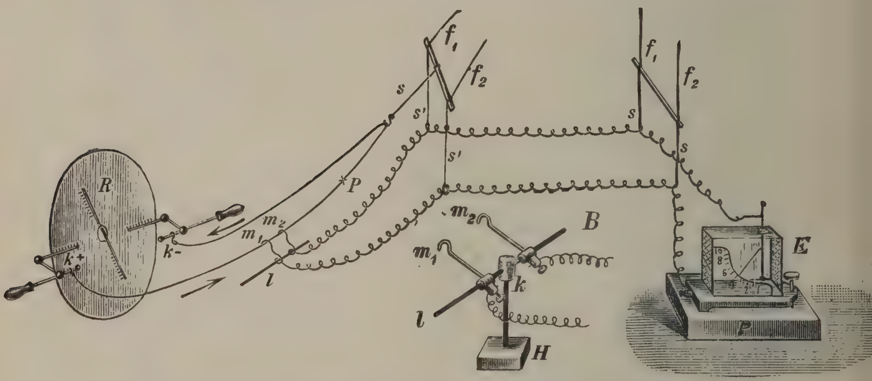


FIG. 81.—Fall of the electric current in a circuit, $\frac{1}{20}$ natural size. B, wire-fork—the pillar in the stand H is movable.

copper wires, and, carrying their ends over small hooks, which hang from the ceiling by silk threads, I attach one of them (m_1) to the binding screw of the electrometer case, and the other (m_2) I connect with the conducting rod of the electrometer.

Now, while one of you kindly turns the handle of the influence machine slowly and regularly, I place the wire-fork (as the instrument described above is named) on the hempen cord, as shown in fig. 81, and immediately you notice a divergence in the leaves of the electrometer, which remains almost entirely un-

changed, if I push the fork about, or along the whole length of the string. At the same time the wire (m_2) laid on a point down stream and connected with the electrometer continually exhibits, when tested, $-$E.

Now I turn the ebonite rod so that m_2 remains where it was, but m_1 is placed at a point down stream—the electrometer still shows the same divergence, but + E. Also, if we move the wire-fork along the cord, the divergence remains almost the same. If we allow for the fact that the machine does not always work quite regularly, and that the cord in places is thinner or twisted more tightly than in others, we may take it that with an almost constant source of electricity the fall of the current in a uniform conductor is constant throughout the whole circuit.

Ratio between fall of current and length of the conductor.

We will now repeat the experiment with a little variation. The cord is 210 cm. in length. At a distance of 70 cm. from the positive conductor, *i.e.* at about $\frac{1}{3}$ of its whole length, a point is marked with a lead pencil (P, fig. 81). At this point I fix a binding screw and connect it to earth by a wire. When the machine is in motion this point (P) of the circuit will take the degree of electrification of the earth, which is zero. In reality you see that at this point the proof electroscope shows no divergence. On the other hand, from P to $+k$ it exhibits +E, and from P to $-k$ always $-$E. I place the wire-fork on the string and the action is the same as before; also if I place the wire m_2, connected with the electroscope, on the zero-point P. But now a remarkable thing happens. In each of the two unequal

parts of the string (*i.e.* between $+k$ and P, as also between P and $-k$) the electrometer gives an almost unvaried divergence; but in the smaller part it shows 3·4, and in the larger 1·8 divisions of the scale: that is to say, in the shorter conductor the fall of the current is almost twice as great as in the larger one. The latter is twice as long as the former, and hence we see that: *in homogeneous conductors of unlike lengths, the difference of level between every pair of equally distant points is inversely proportional to the length of the conductor.*

Electro-motive force.

The work at the expense of which the electricity of the machine is in this case generated (p. 112) is, as we know, the work of the muscles of your fellow-pupil, who is good enough to turn the machine. The force which drives the electricity through the conductor we may call the *electromotive force*, just as before we called the force which set the water in motion the *aquamotive force.* As a measure of the aquamotive force we took the difference of level which occurred when the sluice-gates were shut and the stream continuous. In the same way, as a measure of the electromotive force we may take the difference of electric level (or *potential difference*) at the free poles of the source of electricity.

In order to determine the electromotive force of the influence machine, we must measure the potential difference at the free poles while the machine is working uniformly; but for direct measurement the means we have had at our disposal hitherto are not sufficient. The scale of our electrometer when the normal condenser (since the multiplying power of the condenser is about 200) is used, only registers up to

10 volts,[1] or up to 2000 volts without the condenser. But in this case we shall have to deal, according to the length of spark, with a polar difference or electromotive force of 10–50,000 volts. Yet we can estimate *approximately* by measurements in the electric field the polar difference (electromotive force) of the influence machine (*cf.* Appendix, 12, p. 390).

The Braun electrometer employed by us is too expensive for ordinary use. By replacing the little paper leaf with a small leaf of aluminium of adequate thickness, we can adapt our ordinary electrometer to the required range; yet graduation in this case is scarcely possible, when the apparatus usually found in science classes only is available, and an ungraduated instrument is of no use. We must, therefore, employ in our further experiments other means of generating electricity; but first let us review our past work.

We learnt in static or frictional electricity that:

An electrified insulated conductor bears on its entire outer and inner surface (as also in the hollow within) the same degree of electrification, and therefore a constant potential. On the other hand, in current conductors we find a fall of potential, which, for the sake of clearness, we have named the fall of the electric current, although we are ignorant as to what is moving in the conducting wire. In what, then, does the difference between static (at rest) and dynamic (flowing) electricity consist?

[1] The volt is the practical unit of potential difference and also of the value of the practical work of the degree of electrification. Thus 1 volt $= \frac{1}{300}$ electrostatic potential units (*cf.* pp. 158, 159). It is also used, as we shall see later, as the unit of the polar difference (or, more accurately, of electromotive force).

As an introduction to our study of dynamic electricity, I have purposely chosen a source of electricity before used for the generation of static electricity. Without further discussion you will, therefore, agree that in both cases the same kind of electricity was at work. Hence, when we make use of a new source of supply, no matter of what kind, and which, in the main, exhibits similar phenomena, then we must allow that, figuratively speaking, both in dynamic and static electricity there exists one and the same thing,—in short, that there is only one kind of electricity. The difference between electrostatic and electrodynamic phenomena, therefore, depends solely upon the different action which this same electricity exercises when in a state of rest and in one of movement. It is quite immaterial what means are employed to set in motion (or to cause to flow) the electricity in the conductor concerned.

If, for example, I wave the electrified flint glass rod above an uncharged electroscope (fig. 23, p. 45), while the glass rod is brought near to the ball of the electroscope, the opposite kind of electricity is drawn into the ball by influence and the same kind is driven into the conducting rod and into the leaves. In the same measure as the influencing body is withdrawn, the electricity flows back again from both ends of the conducting rod. Here, then, we have electric currents flowing backwards and forwards in each half of the conductor of the electroscope. In like manner, if we touch an insulated electrified conductor, and so connect it to earth, the electricity flows from the whole outer surface to the point touched and then streams away. The opposite process takes place when

a conductor is being charged. We may therefore state: *an electric current always sets in when, at any point of a conductor, the degree of electrification* (i.e. *the potential*) *is changed.*

In the experiment shown in fig. 81 we agreed to say that electricity *flows* through a conductor, and called the process which takes place when an electric surface of higher level strives to adapt itself to a lower level, the *electric current.* According to the one-fluid hypothesis, the phenomena already observed may be easily explained. For the sake of convenience we will retain the expression − E; but by the term *direction of current* we shall understand the direction in which the + E flows through the conductor. In doing this, as is the general usage, we assume with Franklin that + E stands for vitreous electricity. This is a quite arbitrary distinction, but it is one familiar to us.

Current direction.

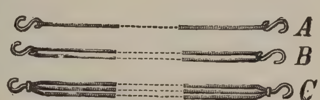


FIG. 82.—Current conductors of different sections.

We will now examine what effect the thickness of the string has upon the fall of the current. For this purpose I have here (fig. 82) three hempen cords, the ends of which are wrapped in tinfoil and bound with copper wire, ending in each case in a hook, which I can couple to the poles of the machine. All three cords are of the same length. The first (A) consists of one strand, the second (B) of two, and the third (C) of three, all cut from the same piece and as far as possible of the same thickness. I fasten the cords to the machine in turn (*s*, fig. 81), and determine with each of them the electric potential at the points of

contact of the wire-fork (the distance between the prongs of course remaining the same). While the machine is turned as regularly as possible, we note the following degrees of divergence on the electrometer: with A, 8·5; with B, 5·5; with C, 2·7. From this we gather that: *the difference of electric level between every two equally distant points of the current decreases, if the section of the current conductor is increased.*[1]

I now place before you a charged paper electroscope (fig. 83). With one hand I take hold of the single

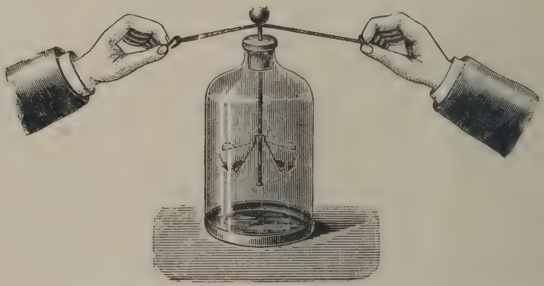


FIG. 83.—Conductivity of cords of varying thickness, ⅐ natural size.

cord (A, fig. 82) by one of the wire hooks, and with the other hand I hold it at a point about 30 cm. from the first hook, and put the middle of the cord held against the conducting rod of the electroscope. You see how the leaves fall together slowly. I repeat the experiment with an equal length of the double cord B: the leaves fall together more quickly, and still more quickly when the three-strand cord is substituted. Hence we see that the three-strand cord conducts

[1] The current may be regulated by putting in circuit from one to ten incandescent lamps in parallel. For safety it is better at the same time to put in the switch-box a lead wire, which will fuse when the intensity of the current becomes too great.

better than the double one, and the double one better than the single one.

We can express what has been observed above more accurately as follows :—

For a particular length of circuit the difference of electric level of the ends is smaller the greater is the conductivity of the conductor.

Some of the results of our observations are interesting. What will happen if we use a good conductor, such as a copper wire, instead of the string? Evidently the difference of electric level on our wire fork will be imperceptibly small. Experiment confirms this. You see, therefore, why I use string. But if I connect the pole of the machine by an *insulator* (non-conductor), the entire electromotive force appears as potential difference at the poles, and the insulator acts in this case as the closed sluice in the canal.

CHAPTER II

Electrification of metals by contact with fluids. Action of two metals simultaneously immersed. Voltaic element or cell. Polarity. Cause of the electromotive force of the cell. Chemical theory. Historical. Volta's contact theory. Constant cells. Arrangement of cells in parallel and in series. Electromotive force of battery in parallel or in series. Comparison of electromotive force of some constant cells.

We have now seen something of magnetism and dynamic electricity. In order to have a bird's-eye view of the important points contained in the last chapter, let us arrange them as concisely as possible.

Retrospect. (1) The magnetic and electrostatic laws of repulsion, attraction, and influence, exhibit many points of striking similarity, but at the same time great differences. For instance, a magnet has always two opposite poles; a magnet divided and subdivided exhibits in all its pieces the properties of a complete magnet, each piece having two poles. Only certain substances (iron and its ore, nickel, etc.) are magnetized with any ease, while all well-insulated solid bodies are capable of being electrified.

(2) Between a conductor, through which electricity flows, and the current of water in a canal there is a striking analogy, which continues even if the conduction of the current is interrupted, as when, in the case of the canal, the sluice is closed. In the

electrical machine an electric potential difference sets in at the ends of the pole wires or electrodes, which is dependent on the *electromotive force* of the apparatus and may be employed as the measure of the E.M.F.

(3) If at the points A and B a difference of electric potential occurs and is maintained when A and B are joined conductively, the electricity evinces a tendency to equalize the differences. The process by which this comes to pass is called the *electric current.* In the conductor which connects both poles of the apparatus, the degree of electrification—that is, the electric difference from the zero level of the earth—differs. The positive electricity + E is strongest at the positive pole, but decreases constantly until at one spot it reaches zero, and, thenceforward, until it reaches the negative pole, the current exhibits a constantly increasing − E. Hence in the current conductor we have a fall of electricity or *fall of potential.* If the current conductor is uniform, the fall is constant, *i.e.* the difference of potential is equal in points at an equal distance from the conductor. In the case of two points at a fixed distance from each other in the circuit, the less the conductivity of the body, the greater is the difference of potential.

We are now going to make the acquaintance of a new source of electricity which at first sight appears unpromising and meagre, but is in reality capable of supplying much greater quantities of electricity than the largest possible electrical machine, and is very generally employed for practical purposes.

I screw on the aluminium electrometer (fig. 84)

a zinc disc, and lay cross-wise upon it two thin strips of mica (*g*), somewhat longer than the diameter of the zinc, varnished on both sides, or instead warmed and rubbed gently with paraffin. Upon these I place a piece of filter paper (*f*) and allow a few drops of diluted sulphuric acid to drop on it.

Now I get a piece of pliable zinc wire (*d*) (or a narrow strip of sheet zinc), provided with a small handle (*i*) of sealing-wax at each end. Bending the wire, I touch with one end the zinc plate (*zn*) and with the other the damp filter paper (*f*). Upon taking away the zinc wire and lifting up the upper strip of mica, the electrometer indicates a weak charge of −E (in fig. 84 the position of the leaves is marked by dotted lines), while the filter paper shows +E.[1]

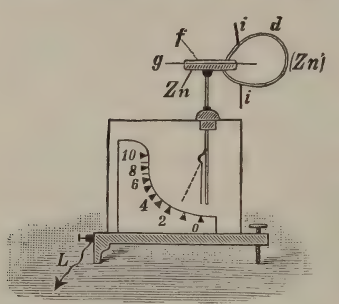


Fig. 84.—Buff's demonstration of the electrification of metals by contact with fluids, $\frac{1}{10}$ natural size.

Let us repeat the experiment with a copper wire and a copper plate. We again get on the electrometer −E, but in much smaller quantity, whereas platinum would give +E. If, instead of the diluted sulphuric acid, we employ water or a solution of salt, the action of the several metals is somewhat different, as far as concerns both the magnitude and the sign of the charge; but zinc, of all metals, when brought into

[1] Both here and in the succeeding experiments with the electrometer its case must be connected to earth by the wire L in fig. 84. Also a clear image of the scale should be projected on the screen (see figs. 13, p. 28, and 16, p. 32).

contact with a suitable fluid, yields the strongest charge of negative electricity.

What will result if two different metals are brought into contact with the same fluid?

Here are some rods of different kinds of metal, as also some of gas-retort charcoal, to the ends of which are soldered flexible copper wires. The wires of the

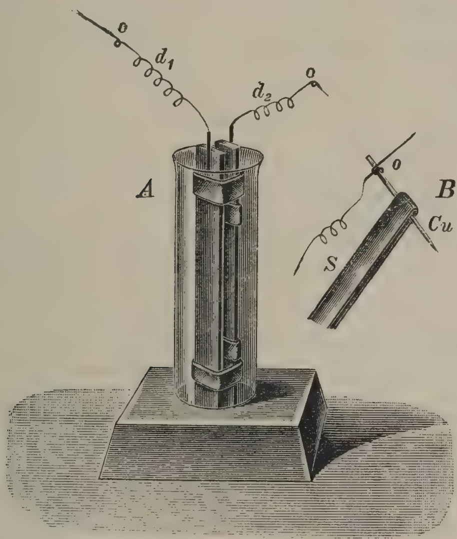


FIG. 85.—A, small voltaic element, ½ natural size; B, connection of conducting wire with an insulated wire.

zinc rods are bound round with green silk and the others with red silk. On each rod there are two rubber bands, so that when placed near each other, their surfaces will not touch.

Now I place a zinc-copper couple in a glass beaker (fig. 85), half filled with diluted sulphuric acid, and set it in a hole in a wooden stand, and we have what is called a *Volta's element* or voltaic cell. Strong German silver wires are soldered to the ends of the Volta's element.

conducting wires (d_1 d_2); and these, after being formed into loops (o), are drawn out into points.

If now I put the point of one German silver wire into the loop of another element, the two rods are placed in actual conductive connection or contact. This is here of the greatest consequence, as you will see later. Next I fix in each of the loops of the electrodes or wires attached to the rods of the cell a wire nail, pushed through one end of a stick of sealing-wax (B, fig 80). These are to be used as handles (S), and by grasping one of them I can hold the pin to the earthing wire of the electrometer without touching the conducting wire of the cell.[1]

I shall take this precaution in all experiments with the electrometer without further mention.

Now let us see if our "element" works. I touch the conducting wires in turn with the ball of the aluminium electroscope—no perceptible action results. Either no electricity at all has been generated or the electrometer is not sensitive enough. We must therefore use the condenser (pp. 68 *et seq.*).

After taking off the ball, I screw upon the electrometer one condenser plate and put the other plate upon it. Now, taking hold of the insulating handles of the wires, I touch simultaneously for a moment the conducting wire of the electrometer and that of the upper plate (fig. 86). Now I lift up the upper plate, and you can see that the electrometer indicates a divergence of nearly two divisions of the scale (more

[1] More suitable than sealing-wax are handles of thin ebonite, about 70 mm. long and 5–6 mm. diam. Near one end a hole is bored with a red-hot steel wire, and the tinned copper wire pushed through.

exactly 1·7). In this case the wire leading from the copper touched the conducting rod of the leaf. Testing by an electrified glass or ebonite rod shows us that the electrometer is charged with + E.

To check this experiment, I will touch the conducting rod with the wire leading from the zinc plate, and the one above with that coming from the copper. The divergence is nearly exactly the same, but shows − E instead of + E, and on repeating the experiments, we constantly get the same results.

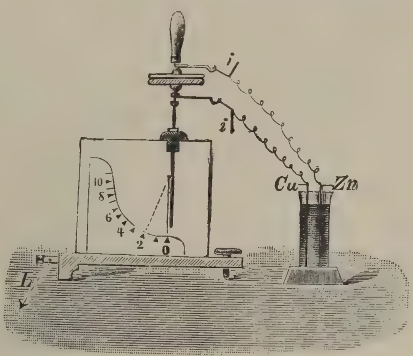


FIG. 86.—Demonstration of the polarity of a voltaic element, $\frac{1}{10}$ natural size.

Hence we learn that: *when two different metals are simultaneously immersed in a suitable fluid, at the protruding ends of the metals, a difference of potential arises and is maintained, whereby one metal (here copper) shows + E, the other (zinc) − E.* Such an element or cell is therefore a self-acting electric machine in miniature. The oppositely electrified metal rods, projecting out of the fluids, form the *poles*, and hence we call the conducting wires fastened to them the pole-wires or *electrodes*. Element.

The difference of electric level or polar difference is, in the case of a cell of this kind, extraordinarily small. Hence, a momentary touching of the electrodes with the plates of a large condenser is sufficient to impart to them the same potential as the poles possess. If Polar difference.

you remember how slow is the charging of a condenser, such as a large Leyden jar, with the help of a glass rod, or even by means of an electric machine (see pp. 88 and 116), it will strike you that now we have come across a source of electricity of low degree of electrification, but in comparison with electrostatic sources of supply, of large quantity, as will be evident later on.

Figuratively speaking, the electric current generated by the influence machine resembles many drops of water which follow each other very closely, and when they have been collected, are forced out with great power and velocity, as from a syringe, while the electric current of our cell flowing through the connecting wire is like a large volume of water gliding onwards with an almost imperceptible fall. The jet of a strong fire-engine has the power to demolish a brick wall; but, on account of the slight pressure it is able to exert on a comparatively small surface, it cannot turn a mill-wheel. We shall, therefore, expect that, under certain circumstances, our "element" will show much greater dynamical effects than the influence machine, and this you will soon see.

We have learnt that the difference of electric level or polar difference at the free poles of the source of electricity furnishes a measure of the magnitude of the *electromotive force* of the apparatus. Now, with the help of the condenser before used for the construction of the graduation scale, we have found the polar difference of our voltaic copper and zinc cell to be 1·7 degrees. After a few minutes' rest, I repeat the experiment, and find it is only 1·3. I connect the electrodes in the way before mentioned (see B, fig. 85)

so that a closed circuit is established (copper, wire, zinc, diluted sulphuric acid, copper), and after a few minutes I again measure. The divergence is scarcely 0·5. Once more I close the circuit for about ten minutes, and the polar difference is only 0·3, that is to say, the electromotive force of our cell has decreased quickly, and the action of the cell *is not constant.* What now is the source of the electric current generally, and why does its action decrease? To decide these questions we must endeavour to follow the process in

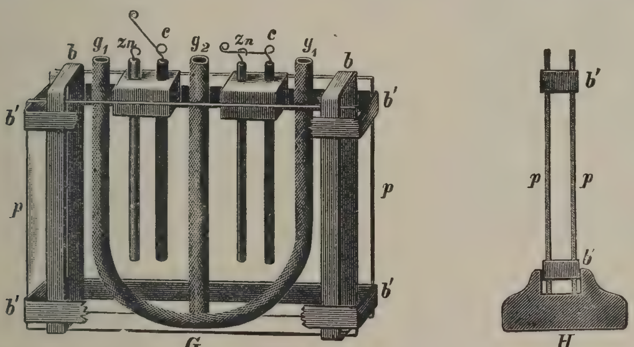


FIG. 87.—Cell arranged for projection, ½ natural size. Two pairs of zinc and copper rods are immersed. The two on the right are connected at the top. The rubber bands are cut away in the left-hand figure.

the interior of the cell, or at least to examine what changes take place in those parts of the two metals which are immersed.

A flat glass trough (G, fig. 87) is furnished with two plates (6 × 9 cm.) of plate glass with smooth edges, in such a way that a piece of strong rubber tubing, arranged in the shape of a horse-shoe (g_1) with an upright centre-piece (g_2), is placed between them. These are kept in position by four thick rubber bands (b' b'), and the whole stands in a groove in a wooden block (H). In the interval between the ends of the rubber tubes

I fix corks, and through them I put a couple of rods, of zinc and copper. Each zinc rod has a hook soldered at its top, and each copper one a spring wire loop. If I bend the latter under the hook, the cell is connected up.

Now I place the apparatus on the projection table (fig. 88), and pour in, without connecting up, diluted (10 per cent.) sulphuric acid through a small funnel. You notice no particular action as yet. But immediately I link up the right cell (*b*) on the left of the projection (S, fig. 88), you see a vigorous movement in the liquid, and to the copper rod, marked by a loop, bubbles attach themselves, which presently envelope it, and then sink down again.

A few moments later, I take out the rods and wipe them—the copper wires are unchanged. The zinc rod of the cell which was not closed, exhibits hardly any sign of action; whereas, the other looks as if it had been eaten away and is in parts black. I amalgamate the zinc rods: that is, I immerse them in diluted sulphuric acid and rub upon them a drop of mercury, so that the zinc surfaces, as far as they are to be immersed, appear as if silvered over. If I *now* repeat the experiment, the result is the same, but both rods remain bright. If, however, the cell is closed for some time, we notice that the zinc rod gradually grows thinner. We therefore conclude that the *zinc rod is being used up.* The action is the same if zinc and carbon are immersed in a solution of bichromate of potash. At the side where the cell is closed, the fluid becomes visibly darker.

Chemical experiments have proved that the little bubbles which ascend from the copper rod, and almost cover it, consist of hydrogen, while the

fluid becomes zinc sulphate ($ZnSO_4$). The bubbles charged with +E, surrounding the copper rod, hinder contact with the fluid and generate an electric counter-pressure which we shall know later under the name of "electric polarization." This gives us the clue to the weakening of the electric current in the

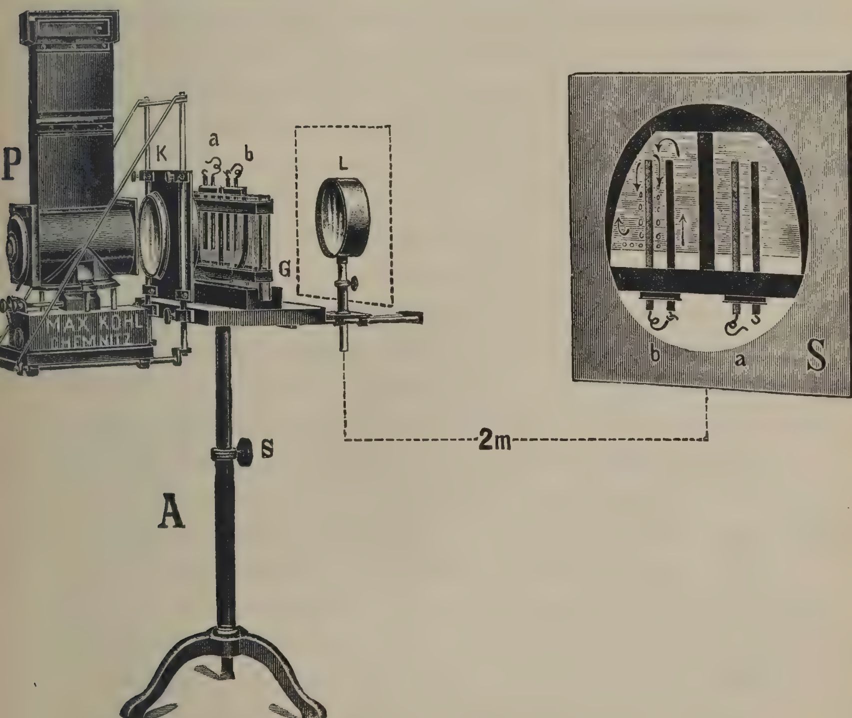


FIG. 88.—Projection of a voltaic element, $\frac{1}{13}$ (the scale $\frac{1}{20}$) natural size. *Cf.* Appendix, 24, p. 398.

voltaic cell; but whence comes the electric current of the cell: that is, where is the seat of the excitement of electricity?

Chemical theory of the electric current.

Zinc has been decomposed—that is, changed into sulphate of zinc—therefore zinc has taken the place of

the hydrogen which was set free. Experiment also proves that, in the case of any combination of two metals dipping into diluted acids, an electric current only arises when chemical action takes place, and then $-E$ always appears at the protruding end of the rod which is most strongly attacked by the acid. And further, as it was shown that the electricity generated increases in proportion to the amount of metal used, we may take it for granted that the chemical action of the fluid on the rod affected, or, better, the action of the metal upon the fluid, is the cause of the excitement of electricity. In fact, the chemical energy liberated by the apparent decomposition of the zinc is the cause of the electromotive force, or, more accurately, of the electric energy. This view, adopted by us, is called the chemical theory of the electric current (De la Rive and Faraday, 1836).

Historical: Galvani.

When Louis Galvani, professor at Bologna, discovered accidentally in 1789 that an observation which had already been made by Coldani in 1756 was correct, or perhaps discovered it anew—namely, that recently killed frogs, when brought near a discharging electrical machine, exhibited a twitching of the limbs—he determined to probe this phenomenon further. Accordingly, he hung upon a copper wire connected with the iron balustrade of his balcony the prepared legs of a frog. As soon as the wind blew them against the balcony, they jerked convulsively, and Galvani imagined that he had discovered a new kind of electricity, flowing like a fluid between nerves and muscles. This, however, proved a mistake.

Volta's contact theory.

As you will understand, the main action in the above case is, the connection, through the moist

muscles of the frog, of two different metals. The credit of first noticing this is due to Volta, the discoverer of the condenser, and professor at Pavia in 1793. He discovered that mere contact between two different metals was quite sufficient to charge the two of them with opposite kinds of electricity. According to this, contact between two different metals is the main cause of the electromotive force, and the stratum of fluid is of only secondary importance. The contact theory only gained the victory over Galvani's theory after severe struggles and the slaughter of many innocent frogs, and (although in a different form) it has at the present day many followers.

Recent observations by Exner, Ostwald, and others have established as a fact that during the apparent contact of two plates of different metals (Volta's "fundamental experiment," *cf.* Appendix, 25, p. 399), a microscopic stratum of moisture or of condensed gases plays an important part in bringing about the difference of electric level in the metals, and that the nature of the gases surrounding the plates before contact has great influence not only upon the magnitude, but also upon the sign of the charge of the two metal plates. Hence we shall confine ourselves to the chemical theory, and not go any further into the contact hypothesis. This we do with greater readiness, because the chemical theory is the simpler, and the choice of a theory has no influence on the understanding of what is to follow.

Dynamic electricity generated by means of a cell is called, in honour of Galvani, "galvanism," or galvanic electricity. Yet a more appropriate name would have been voltaic electricity, and in fact many

men of science call it by this name. Before the chemical theory arose, it was also known as "contact electricity," and this expression is still frequently found.

Let us now return to our experiments.

We observed the troublesome effect of the hydrogen upon the copper. Cannot the formation, or at least the accumulation, of this gas be hindered? Certainly

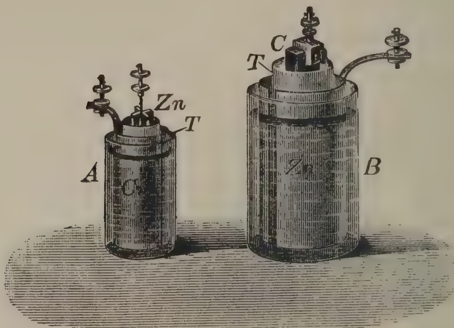


FIG. 89.—A. Daniell's cell [zinc (Zn) in 10 per cent. sulphuric acid (or in a solution of zinc sulphate); copper in saturated solution of copper sulphate], $\frac{1}{10}$ natural size. B. Bunsen's, $\frac{1}{10}$ natural size. Carbon (C) in solution of bichromate of soda; zinc (Zn) in diluted sulphuric acid.

it can, and chemistry furnishes us with the very means of doing this. Blue vitriol or sulphate of copper ($CuSO_4$) is easily soluble in water. If we dip the copper rod in a solution of sulphate of copper, separated from the diluted acid by a porous vessel, in which the zinc rod is placed, no hydrogen bubbles appear; but copper is set free from the solution and precipitated upon the copper rod. To this we shall refer again later. A, fig. 89, illustrates a cell of this kind invented by Daniell in 1836, in which a porous cylinder T separates the two fluids.

Daniell's cell.

This cell is very constant, especially if the zinc is amalgamated and stands in a solution of zinc sulphate in water instead of diluted sulphuric acid.

Still more effective is the constant Bunsen's Bichromate cell, which in appearance is the same as Daniell's (B, fig. 89). Instead of copper, a plate of gas charcoal, dipping into a solution of bichromate of soda, is used. The amalgamated zinc is immersed in diluted sulphuric acid. Usually the outer zinc cylinder, in this arrangement, has a copper strip Bunsen cell.

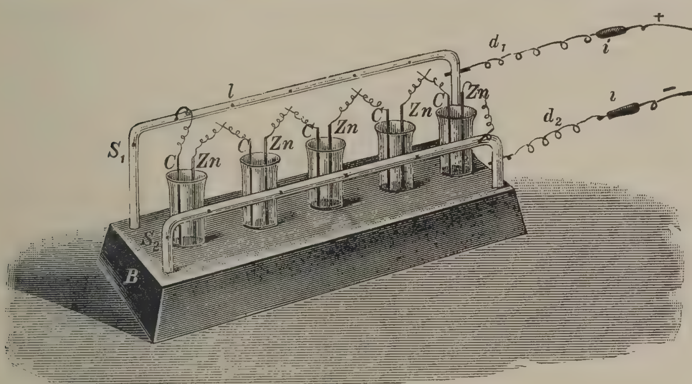


FIG. 90.—Simple immersion battery, ⅓ natural size.

soldered on to it, to which is fastened the binding screw for the conducting wire. If sulphuric acid be added to chromic acid (*cf.* Appendix, 26, p. 400), it is only necessary to immerse the two plates (Zn and C) in a solution such as this, to keep the action of the elements more or less constant for a long time. By this means we have the power of setting up a very convenient immersion cell, of which, later on, we shall often make use (see also fig. 116, p. 250).

Before you is a small *immersion battery* (fig. 90). Its cells resemble that described above (fig. 85, p. 193),

except that for the copper rod a carbon one is substituted.[1] The rods are insulated by rubber bands. A small wooden slab B contains holes into which thick glass beakers are inserted. Two brass rods (S_1 S_2) have conducting wires (d_1 d_2) at the ends, and six holes (l) are bored along the sides of each rod, into which the conducting wire and the electrodes of the several cells may be fixed.

Wood as an insulator for galvanic currents.

As you perceive, the brass rods are separated only by a length of wood, and yet it is quite sufficient to insulate them from each other—that is, in the case of the galvanic current. When the sources of electricity drawn upon are of a high degree of efficiency, as, for example, the influence machine and the dynamo which we shall meet with later on, then the insulation would not be anything like good enough, as the pressure exercised by the electricity in its endeavour to effect a junction increases in proportion to the polar difference.

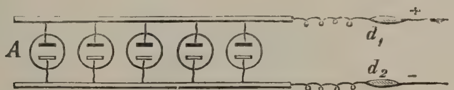
For electrodes we make use of red and green flexible cords, such as are used with portable electric lamps, each end of which is soldered to a tinned brass wire 60 mm. long and $1\frac{1}{2}$–2 mm. diameter.[2] Pieces of

[1] For a space of about 8 mm. the upper end of the carbon rod is coppered (electrotyped), upon which, when properly dried, the soldering of the wires is easily done. The employment of pure tin as solder is, in this case, as with the wires, very advantageous, although soldering with it is more difficult. The cleansed soldered place remains bare.

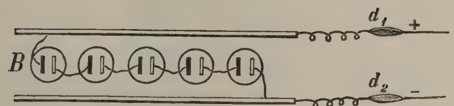
[2] The free ends of the tinned wire are first bent into a spiral circle with a diameter radius of about 3 mm., the slightly pointed ends of 15 mm. hammered flat, and bent back in the original direction. In this way the wire is easily fixed in the clip or in the ordinary pierced binding screw. The first method gives much safer contact.

silk ribbon of the same colour are bound tightly round the solderings. In all cases the positive pole will be connected by means of the red-covered wire, and the negative by green, so that the kind of connection can be seen from a distance.

We will first estimate the polar difference (and at the same time the electromotive force proportional to it) of the cells by the aluminium electrometer. We get, as you see on the projection screen: 1·95; 1·93; 1·95; 1·96; 1·94: that is to say, if exactly the same arrangement is adhered to, the scale



Arrangement in Parallel.



Arrangement in Series.

FIG. 91.—Different arrangements of the galvanic cells in a battery.

indicates—apart from unavoidable errors of reading—an exactly equal electromotive force.

Now comes the question: *Will the electromotive force be changed, if we combine the cells in groups of two, three, etc.?*

Parallel and series grouping.

How, now, shall we arrange them? Two courses are open to us. We may join together all the carbon rods and all the zinc ones (A, fig. 91); or we may join the zinc rod of the first cell to the carbon rod of the next, and the zinc of this to the carbon of the third, and so on (B, fig. 91). The first mode of combination or arrangement is called the multiple arc or parallel arrangement, because it corresponds

to streams of water all flowing into the sea by the same mouth. In the other mode, called arrangement in series, or in succession, the electric current flowing from carbon to zinc passes from cell to cell. Such a group of connected cells is called also battery or chain arrangement.

Now we will connect our cells first in the parallel arrangement and then in series, and observe their effect on the electrometer. At the same time, in order to see the results at a glance, we will tabulate the figures given.

Measurements of the Electromotive Force on the Electrometer.

No. of Cells.	Arrangement.	
	(*a*) In Parallel.	(*b*) In Series.
	Divergence.	*Divergence.*
1	2·0 Unchanged	2·0; $E_1 = 1$.
2		4·0; $E_2 = 2$ (exactly).
3		5·9; $E_3 = 3$ (almost exactly).
4		7·9; $E_4 = 4$ (nearly).
5		9·8; $E_5 = 5$ (nearly).

From this we see that in the case of the parallel arrangement the electromotive force remains unchanged, while in that of the series arrangement it increases with the number of elements and is proportional to it.

We have in the above case employed the same kind of cells. Perhaps if we combine elements of different sorts there will be a variation.

Fig. 92 is an illustration of an easily set up Daniell's cell. The U-shaped glass tube is fixed in a block of wood, and in the bend some loosely packed glass-wool or asbestos wadding is placed, so that the fluids can only trickle through it slowly, and then not be able to mix entirely, by which means the constant working of this cell is favoured. Into one leg of the tube I pour a solution of copper sulphate, and into

Model of a constant cell.

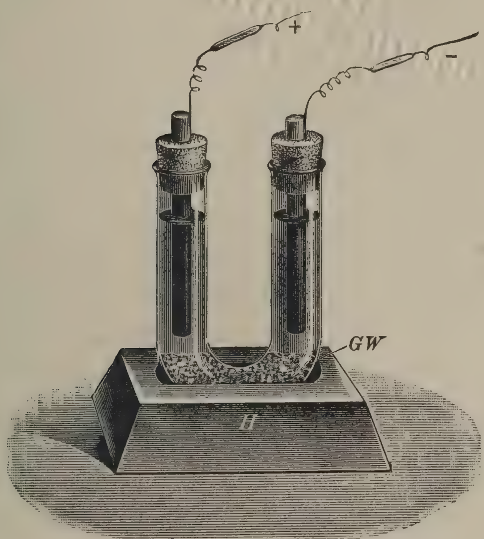


Fig. 92.—Small constant cell, $\frac{2}{3}$ natural size.

the other a solution of zinc sulphate, and push the copper and zinc rods through corks fitting into the tubes. The electrodes have insulated handles (i) of coloured silk cord (p. 205). A similar vessel may be made use of for Bunsen's Bichromate cell (p. 203).

By the *electrometer* we get a measure of the electromotive force (the mean of five readings).

1 Daniell = 1·05 ; 1 Bichromate = 2·0.

The two placed in parallel yield 1·95; in series 3·05 ($=1·05+2·0$).

In the parallel arrangement the electromotive force of dissimilar cells is hardly as great as that of the stronger; but in the arrangement in series it is equal to the sum of the electromotive forces of the separate cells.

What will take place if I arrange the cells in such a manner that the current of the one works against that of the other? For this experiment very constant cells must be used, wherefore I cannot employ the immersion cells as before. I connect the zinc rod of the Daniell's cell with the zinc rod of the U-shaped bichromate cell, and hold the electrode of the carbon to the electrometer plate, that of the copper one to the upper or condensing plate. After lifting off the upper condenser plate, the electrometer exhibits only 0·9 and +E, as the electrified flint-glass rod indicates. Now $0·9=2·0-1·05$ (nearly): that is, the electromotive force when two cells are connected in opposition is equal to the difference of their electromotive forces.

If we let the electromotive forces of the two cells be denoted by E and e, then we may write:

$$\mathrm{E}-e=\mathrm{E}+(-e)=2·0+(-1·05)=0·95 \text{ (observed } 0·90).$$

Therefore, we can state generally:

In the series arrangement of cells, the electromotive force of the battery is equal to the algebraic sum of the electromotive forces of the separate cells.

Formerly the electromotive force of a Daniell's cell was taken as the unit. Now the *volt* is the practical unit (*cf.* footnote, p. 185). 1 *Daniell's cell* = 1·07 *volts.*

VARIOUS FORMS OF CELLS

The number of the various galvanic cells is very great. I am not able to give you examples of all of them, or even of those most generally used. We shall nearly always employ either a Daniell's or a Bichromate cell. Since the shape of the containing vessels is indifferent, with the help of our U-shaped tube, and its division of glass-wool, I will at least set up for you small models of the most important kinds of constant cells, so that we can compare the electromotive force of each with that of the Daniell's cell.

1. *Daniell's cell.*—Copper in solution of sulphate of copper; zinc in diluted sulphuric acid (or zinc sulphate solution).

2. *Leclanché's.*—A mixture of carbon with powdered manganese ore and coke; zinc (amalgamated) in solution of sal-ammoniac (which also fills the free space in the other leg). A very constant cell.

3. *Grove's.*—Platinum in concentrated nitric acid; amalgamated zinc in diluted sulphuric acid. (As nitric acid attacks cork, and so may set free noxious fumes, rubber stoppers must be used.)

4. *Bunsen's.*—(*a*) Hard carbon (gas-coke) instead of platinum, otherwise a Grove's cell. (*b*) Carbon in solution of bichromate of potash: zinc in diluted sulphuric acid (made by Grenet as immersion cell).[1]

5. *Latimer Clarke's cell* (often used as standard cell).—Platinum in solution of zinc sulphate; chemi-

[1] Grenet's cell has no porous pot, and the zinc and carbon plates both dip into the same solution, consisting of 1 part of potassium bichromate, 2 of sulphuric acid, and 10 of water. In England, this alone is called a Bichromate cell. Its invention is attributed to Poggendorff.—*Ed.*

cally pure, *not* amalgamated zinc, in a stiff paste of mercurous sulphate. H-shaped vessels must be used. (A porous diaphragm is not necessary.)

6. *New cell*, invented by *G. P. Bousfield.*—Inside a porous beaker, carbon in nitric acid.—Outside, zinc in solution of soda (*Electrician*, lii., 1904, p. 1024.)

7. *Weiler's cupron cell.* — A plate of oxidized copper suspended between two amalgamated zinc plates in caustic hydrate of soda. This cell has at the beginning an E.M.F. of a little over 1 volt. The electromotive force declines during use to 0·8 volts, and then remains (even when closed for some time) very constant. The copper plate, after being dried in a warm place, is after twenty-four hours again ready for use or regenerated.

8. *The dry cells* consist of zinc and carbon plates embedded in sand, damped with a solution of sal-ammoniac, or in a correspondingly treated mass of gelatine. They are not very constant, but very convenient for use, and relatively very cheap.

To obtain comparative results, we will let all the cells work a short time, that is to say, I will connect their poles by wires, so that the current runs through them for about five minutes and a kind of equilibrium results.

After this we will proceed to measurement, taking care *always to connect the positive electrode directly with the electrometer*, since by variable charging of the condenser plates, disturbances might be caused. (In the following table the electromotive forces are given in volts.)

Electromotive Force of some Constant Elements.

	(a) in Volts.	(b) Daniell = 1.
1 Daniell	1·07 volts.	1
1 Grove	2·0 ,,	1·9 Daniell
1 Bunsen	1·9–2·0 ,,	1·9 ,,
1 Clarke,	1·5 ,,	1·4 ,,
1 Leclanché	1·3 ,,	1·2 ,,
1 Bousfield	2·6 ,,	2·3 ,,
1 Cupron cell	0·8 ,,	0·77 ,,
1 Dry cell	1·3–1·5 ,,	1·2–1·4 ,,

These numbers give you a standard for judging the electromotive force of the cells. As to their use, we must be guided by questions of the *electromotive force*, the *constancy* or the *convenience*, and finally of *cost*. For practical purposes, for the last-named reason, Leclanché's cell is usually employed, while in physical laboratories bichromate or cupron cells are used.

We have thus gained a knowledge of the action of the "open" (*i.e.* not connected by conductors) poles of the cells, and next we shall turn our attention to the *closed circuit.*

CHAPTER III

Demonstration of the fall of the stream in the galvanic current. The commutator. Mutual attraction and repulsion of conductors carrying current. Ampère's parallelogram. Directive action of movable conductors and solenoids. Reciprocal action of two conductors. Effect of magnet upon a movable conductor. Directive action of a solenoid. Electro-magnets. Deflection of magnetic needle by galvanic current. Ampère's swimming rule. Law of direction of current. Ampère's hypothesis of magnetism. Lodge's experiment. The galvanoscope. Difference of readings of galvanoscope and electrometer. The multiplying galvanometer. The solenoid galvanoscope. Difference of dynamic action in a galvanic cell and an influence machine.

In the preceding chapter we learned the existence of a new source of electricity. We saw that, under certain circumstances, metals, when brought into contact with fluids, became permanently electrified. But the degree of electrification attained thereby was so small that we had to call in the aid of the aluminium electrometer and its condenser to convince ourselves of the presence of free electricity at the protruding ends or poles of the conducting wires. We learned that:

Retrospect. (1) If two metal rods are dipped simultaneously into a suitable fluid, the protruding end of one of them receives a charge of $+E$, whilst the other indicates $-E$. This difference of electrical polarity was immediately restored after the pole had been conductively touched, and continued so long as the chemical action was unweakened. *Hence in chemical*

action we discover the cause of the electromotive force of the cell.

(2) The difference of electric level of the free poles of a galvanic cell forms a measure of the electromotive force; but the *volt* is the practical unit of electromotive force. A Daniell's cell corresponds to 1·07 volts, a freshly charged bichromate cell to about 2 volts.

(3) If several constant and similar galvanic cells are arranged in parallel, the electromotive force is the same as in a single cell; but when they are arranged in series, the electromotive force increases according to the number of elements. If the latter are of unequal electromotive force, then in the arrangement in parallel the entire electromotive force of the battery equals the algebraic sum of the single cells, as also is the case when single cells are coupled together in pairs.

So far our experiments have been confined to the proof of electricity at the free poles of the galvanic cells. We will now follow—as we did in the case of the influence machine—the fall of the current in a closed circuit.

But as, according to our experience, the difference of level of the poles decreases very quickly if conductive connection is established and an electric current is thus evoked, and as the polar difference in comparison with the electric machine is very small, we must have a battery or chain of many cells. We will employ small batteries of Daniell's cells (*cf.* fig. 92, p. 207). Ten batteries of five elements each in series will suffice, as we shall thus have the electro-

motive force of one cell increased fifty fold. In A, fig. 93, you have the illustration of a small battery of the kind. By means of the wires d_1 d_2 fitting into the holes in the brass stands, we connect the five batteries together. The wooden block H gives them more stability, and at the same time makes them more portable, and we are also thus able to use groups arranged in parallel.

We still require a suitable conductor. Here (R, fig. 94) you see hanging by two strings, over the

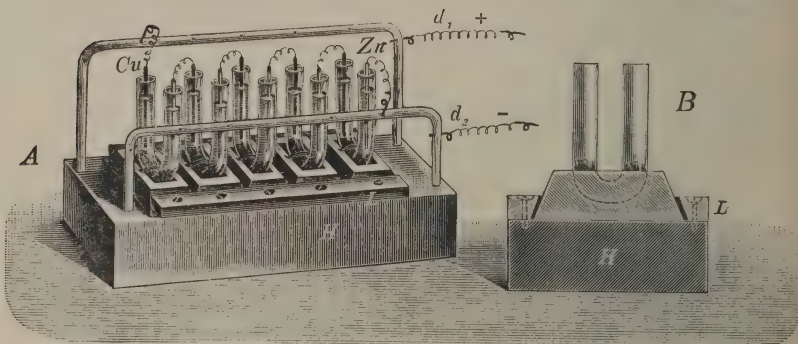


FIG. 93.—Small battery of 5 Daniell's cells. A, $\frac{1}{8}$; B, $\frac{1}{2}$ natural size.

experiment table, a wooden frame, on the upper side of which ten German silver pins are screwed, and on the lower one eleven. Their protruding ends are pointed, so that each fits into the aperture of a plug-switch (KS II.).

A manganin wire of 10 m. long and 0·6 mm. thick is divided, as nearly as possible, into ten equal parts. Beginning at the lower part of the frame, I fasten each division point to the pins (0, 1, 2, 3, . . . 10); then, taking hold of the middle of each of the parts hanging down, I hook it on to the corresponding pin at the top of the frame. Thus the whole wire forms

a pretty long conductor. Pins 0 and 10 I connect by means of flexible wire cord with the battery B of fifty cells, but only during the time of measurement.

With two thin silk-covered copper wires, each having one end fastened to a plug-switch, whilst the other carries a small handle (*ii.*) of sealing-wax, I am able to connect together every pair of pins for a moment, in order to decide the difference of level between these two points in the current. Between the points 0 and

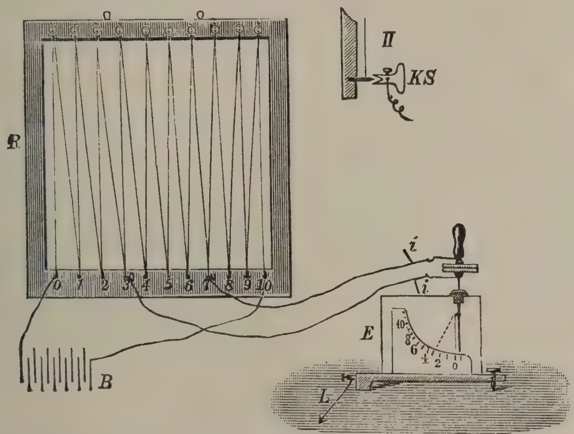


FIG. 94.—Proof of fall of stream in conductor, $\frac{1}{15}$ natural size.
R. Conductor ; B. Battery of 50 cells ; E. Electrometer ; II. Switch-plug.

10 (fig. 94) we get 8·2 scale divisions. As the whole length of the conducting wire is divided as exactly as possible into ten equal parts, we may expect that, between the points 0 and 1, 1 and 2, etc., the tenth part of this difference of level should be indicated (p. 183). This is in fact the case, for the electrometer shows almost a constant 0·8 : that is to say, *with a uniform current conductor, the difference of level between any two equally distant points in the current is constant.*

This experiment is—on account of the condenser—perhaps open to objection;[1] still, it is sufficient, for the present, to give you an idea of the existence of a fall in the current. It is very difficult to prove, with the few cells at our disposal for this purpose, that the free electricity from one pole (0) to the other (10) constantly decreases. Still, we will try. I connect—for a moment—the plate of the electrometer (fig. 94) with the pin 0, but at the same time I earth the upper plate. After lifting off the upper plate the electrometer indicates $+E = 3{\cdot}3$, but at the pin (10) $-E = 3{\cdot}5$. Between 1 to 5 the charges decrease and are positive; from 6 to 10 they increase and are negative. The zero point in the manganin wire lies between 5 and 6. You thus see that we meet, in the main, with the same phenomena that we observed when we used the influence machine.

We will now go a step further and enquire: What is the effect of the electric current on its surroundings?

First, we will examine whether the conductors, through which the current flows, mutually attract and repel each other, as we observed was the case with electrified bodies—for instance, with the electrified pendulum. With this object we will use very mobile current conductors, and observe whether another conductor, when brought near to them, exercises any influence upon them.

As, later on, we shall frequently be obliged to turn the current into a particular direction, we will make use

[1] Later an apparatus will be shown, which affords a much more convenient and accurate way of determining the fall of potential (figs. 130, 131, pp. 289, 290).

of an apparatus which renders this possible without the necessity of also changing the electrodes. A current changer of this kind is called a *commutator* (fig. 95).

A small cylinder (T) of ebonite, possessing a discontinuous axis whereby the two ends are insulated from each other, is fixed between two brass supports (s_1 s_2) and made to revolve by means of the handle (g). The supports are connected with the binding screws (p_1 p_2) by copper strips. Two metal plates (m_1 m_2) are fitted on the cylinder, and in such a position that, when it is at rest, they are exactly

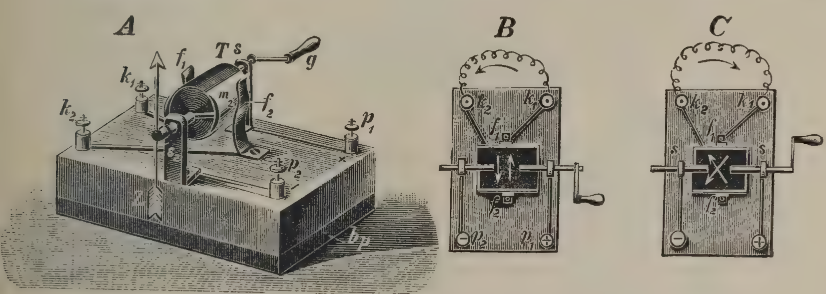


FIG. 95.—Rühmkorff's commutator, with automatic current direction indicator (Z), $\frac{1}{6}$ natural size.

opposite to each other. A copper strip from one axis connects this last with m_1, and another from the other axis connects it with m_2. f_1 f_2 are two brass springs, which press against the cylinder, and are both in contact with the metal plates (m_1 m_2). When the cylinder is in a certain position the springs (f_1 f_2) are joined to the binding screws (k_1 k_2) by strips of copper. If the binding screws (p_1 p_2) are connected to the electrodes of a single cell, and k_1 and k_2 are joined by a wire, then the current flows, in one position of the commutator (B, fig. 95), from p_1 through k_1 to k_2, but in another position of the

cylinder (C, fig. 95) from p_1 through k_2 to k_1; therefore, in the position of the conductor between k_1 and k_2 the direction of the current will be changed, if the handle (g) makes a half turn. In the middle position of the cylinder, the springs (f_1 f_2) are not in contact, hence the current is interrupted. Over the lengthened axis of the cylinder a brass tube is pushed, to which a German silver pointer (Z) is soldered. In fig. 95, A, the pointer or indicator is soldered to a small tube which is pushed over the end of the axis of the cylinder. Then the indicator turns with the cylinder and shows the altered direction of current in the portion (k_1 k_2) (A, fig. 95) of the conductor, as you will see.

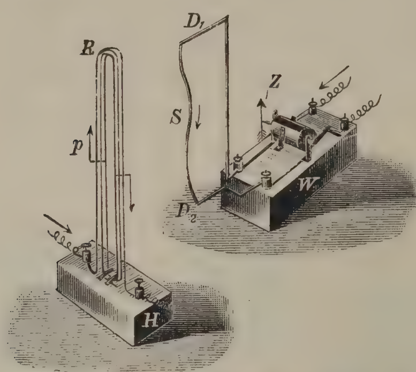


FIG. 96.—Mühlenbein's portable current conductor (S), modified and simplified, $\frac{1}{8}$ natural size. R has fifteen turns of wire.

A movable current conductor is made from a narrow strip of the finest tinfoil, about 28 cm. long, and 5 mm. broad. This I fasten to the ends of conveniently shaped strong brass wires (D_1 D_2, fig. 96), fitted to the commutator. D_1 should be at such a distance from D_2 that the strip S may hang loosely.[1]

[1] At the end of the brass wires (D_1 D_2), which are about 3·5 mm. thick, small slits are sawn about 8 mm. deep, and into these I push the ends of the tinfoil strips doubled up several times; then I bind the outer ends of D_1 D_2 fast with strong copper wire (*cf.* A, fig. 109, p. 234).

If I now connect the other terminals of the commutator (those marked + and −) with the corresponding poles of a bichromate cell (fig. 116), then the current flows in the direction of the indicator (Z) through the tinfoil strip. A fixed conductor is made of silk or cotton covered copper wire. This I bend in fifteen turns to the shape of a frame (R, fig. 96), which I stand upright in a wooden block (H), having bound together the corners with thread. The ends of the wire I lead to terminals, which are connected with a second bichromate cell. To indicate to you the direction of the current, a paper arrow is fixed to each side of the frame.

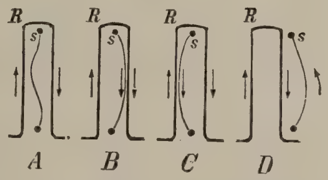


FIG. 97.—Action of a fixed current conductor on a movable one, $\frac{1}{18}$ natural size.

Now I push the wire frame R over the tinfoil strip, which I beg you to observe carefully. While up to this the tinfoil hung loosely down (S, fig. 97), now it is blown out and lies first towards one side and then to the other of the wire frame (B and C, fig. 97), according as I change the direction of the current. It gives one the impression of the tinfoil strip being attracted, first by the R and then by the L half of the frame. A glance at the indicator of the commutator shows that the movable conductor is attracted to that side of the frame where the current has the same direction as itself.

Now I modify the experiment by placing the wire frame quite close to the tinfoil strip and close the circuit. When the current is in the same direction there is attraction, but when it is opposite

there is a distinct repulsion (D, fig. 97). We therefore derive the following rule: *Electric currents flowing in the same direction attract each other, those flowing in opposite directions repel one another.*

If our observation is right, then a current conductor, free to move, will strive to place itself in the same direction and parallel with another which is placed near it; therefore, under certain conditions, it displays a *directing force.* We will now put this to the test.

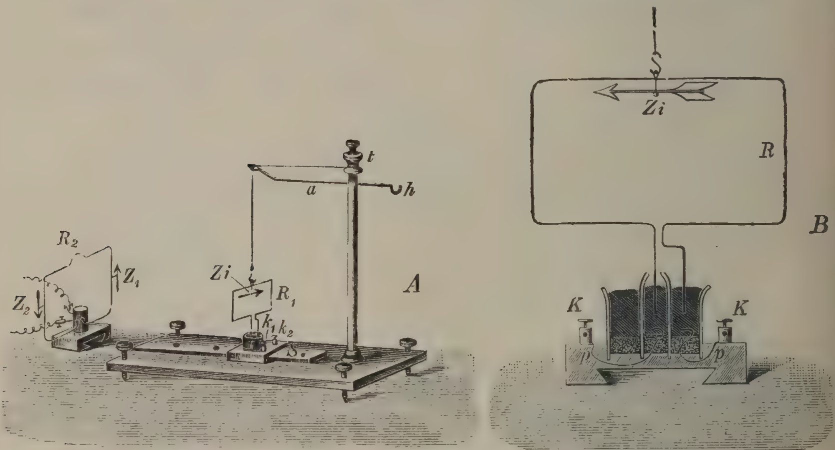


FIG. 98.—Modified and simplified Ampère's parallelogram, $\frac{1}{10}$ natural size. B. Contact cup, $\frac{1}{2}$ natural size. (The platinum should just dip in.) R should consist of ten turns.

An open wire frame, the "solenoid" (R, fig. 98 A), consisting of ten turns of covered copper wire 0·5 mm. thick, is suspended from a fine hair (or from an unspun silk thread), in such a way that the ends, to which platinum points of 40 mm. length are soldered, just dip respectively[1] into two small cups of mercury,

[1] It is recommended to flatten the end of the wire dipping into the outer cup, so that it may turn more easily in the mercury. The wires must dip in very slightly, and the mercury must be very pure.

one inside the other (fig. 98, B). Both mercury cups are insulated from each other, but joined by platinum wires to binding screws (p p), which I put in connection with a bichromate cell by means of the commutator. The thread, which is several times wound round the drum (t), may be shortened or lengthened. A slight turn of the arm (a) renders a sideways movement of the thread and parallelogram possible; while the slide on which the cup stands may be moved backwards or forwards, so that it is always possible to suspend the straight end of the wire perpendicularly over the middle point of the mercury cup, and then the frame can be let down and the circuit closed. A pin fastened to the parallelogram carries a small cardboard arrow, to act as current indicator (Zi). On one side it is painted red, on the other green.

As fixed current conductor, a frame of strong copper wire (R_2, fig. 98 A) will serve; it is fixed in a movable block, and provided with two metal current indicators (Z_1 Z_2). This frame may be moved as near as desired to the movable one (R_1). This apparatus, here modified and simplified, is called *Ampère's parallelogram.*

Now I connect the terminals of the fixed wire frame (R_2) with a bichromate cell, place the indicator inside, and push the frame up to the movable one, so that one vertical side is to the front (A, fig. 99). You see, the movable conductor turns round so that the current in the part brought near flows in the same direction. I turn the fixed frame round 180°, and immediately the movable conductor moves and places itself correspondingly (B, fig. 99). Now I

interrupt the current in the commutator, push the fixed frame so far forward that the middle points of the two coincide, and close the circuit. Immediately the movable conductor swings round, wavers to and fro once or twice, and then places itself so that the currents take up the same parallel direction (Ampère).

Now I connect both bichromate cells in series with the commutator, and therefore with the moving wire frame, and close the current corresponding to the indicator. The ring turns slowly, and assumes such a position that the *arrow points to the east.* Is that merely chance? I turn the arrow through 180° and reverse the current, which new direction is again shown by the arrow; but the result is the same. In both cases the current flows from the top eastwards, or, if you look from the north, in the reverse direction to the hands of a clock. Whence comes this? The wire frame, through which a current of considerable strength flows, exhibits a directing force just like a magnetic needle, except that it assumes with its poles a north-south direction, its plane therefore being west-east. This directing force can—as there is no other cause—only be an effect of the magnetism of the earth. If this supposition is correct, then a magnetic rod brought near must exercise a directing force upon the movable conductor. The test is simple. I approach the south pole of a magnet to the edge of the wire frame (A, fig. 100). Notice

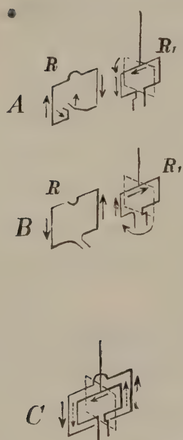


FIG. 99. — Directing force of a fixed current conductor upon a movable one, $\frac{1}{10}$ natural size.

Action of a magnet upon a movable current conductor.

how the ring immediately makes a quarter turn, and offers to the south pole of the magnet the surface which before was pointed to the north. The opposite action occurs if I present the north pole of the

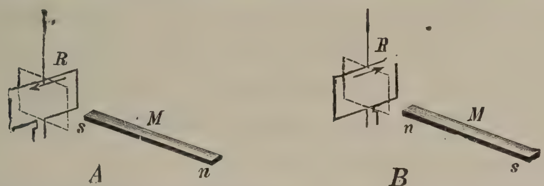


FIG. 100.—Action of magnet on movable conductor, $\frac{1}{10}$ natural size.

magnet (B, fig. 100). This striking phenomenon evidently proves that there exists some relation between the electric current and a magnet. To examine into this is now our task.

I replace the wire frame of our apparatus by a helix of hard and stiff silk-covered copper wire The solenoid.

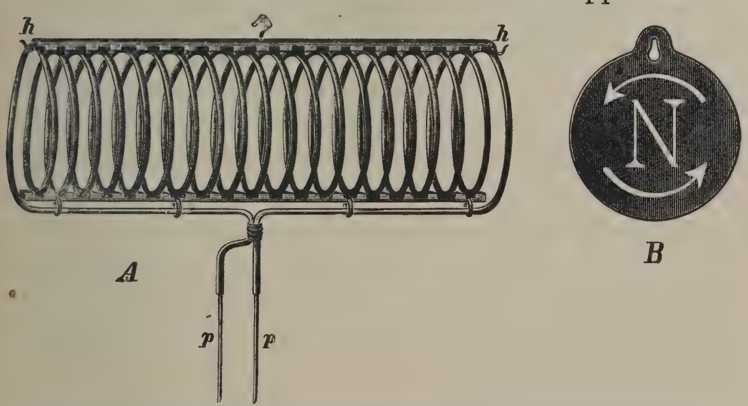


FIG. 101.—Spiral solenoid, with current direction marked, ½ natural size. (Diameter of coil, 50–60 mm.)

(fig. 101), coiled in such a way that the ends meet; they are then bound together with silk threads, and one of them is bent so that the platinum wires soldered to them may dip into mercury contact cup

(*cf.* fig. 98, p. 220). To indicate the direction of the current, I hang two differently coloured paper discs on the hooks (h) of the solenoid. These discs are made of stiff paper, painted one side red and the other green. On the red side an "N" and two arrows, made of white paper, point in the opposite direction to that in which the hands of a clock move. On the green side are an "S" and two arrows pointing as move the hands of a clock (B, fig. 101).

Now I close the circuit, so that the current has the direction of the arrows on the solenoid. Immediately the solenoid moves and puts itself north and south. As a glance at the arrow shows, the stream again flows over to the *east.*

Now I turn each of the paper discs and change the current. Again the red end points north, and the stream again flows, of which we can easily convince ourselves, in the direction of the arrow. Now, I bring from a side direction the north pole of the magnet—the solenoid swings violently round and turns its green end to it, when the current flows as the hands of a clock move. When the south pole is approached the opposite movement takes place. To test it, I quickly present the north pole of the magnet to the red end of the solenoid. This is repelled, and also the green end from the south pole. We gather from this that:

Between a magnet and a solenoid, through which an electric current flows, exactly the same phenomena of polar attraction and repulsion take place as we observed between two magnets; and, indeed, the end of the solenoid, when the current flows in the direction of the hands of a clock, behaves like a south-

seeking magnetic pole; the other end, therefore, when it circulates in the contrary direction, behaves like a north-seeking pole (Weber, Ampère).

Has, then, the solenoid, traversed by the current, become a magnet? I take a glass tube (g, fig. 102) and wrap it round with twenty to thirty turns of silk-covered copper wire (about 1 mm. diameter) and connect the ends with a bichromate cell, but insert in the circuit a switch or key in order to be able to close or open the current at will. This key (S) consists of a wooden block, in which a cup-shaped hole is bored

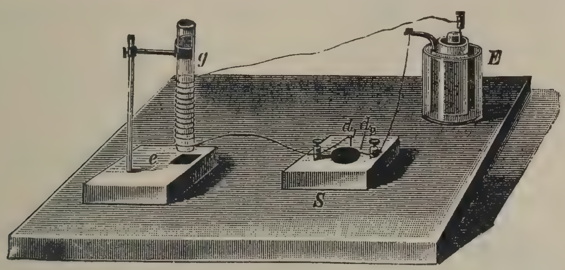


FIG. 102.—Magnetic effect of a coiled wire, ⅛ natural size. S, mercury switch.

and filled with mercury. Two steel wires (d_1 d_2) are fastened so that one dips in deeply, the other, bent into a hook, sways over the surface of the mercury, and so by simple pressure from the finger it may be immersed in it and contact be thereby established.

I hold the wire coil just above a little piece of sheet-iron (e) and close the circuit. The iron is attracted, but falls away again if I break the circuit. Now I bring one end of a suspended magnet needle near: the ends of the needle are attracted, just as if the coil were a magnet, but only for so long as the current flows in it. A coil of wire through which a galvanic current flows possesses veritable magnetic

properties, which vanish without trace if the current is interrupted.

Now comes the question: Can we by means of the electric current form artificial magnets?

Different behaviour of iron and steel.

We saw before (p. 169) that iron and steel conduct themselves differently when magnetized. We will, therefore, test both of them. A wooden frame (fig. 103) has two holes in its upper cross-piece, through one of which I push a bar of soft iron (e), and through the other, one of the same size, of steel (s), and fasten them both with screws. Now I wrap round each rod fifteen windings of silk covered-copper wire, and carry the ends to two binding screws (k_1 k_2), which by insertion of the contact key I connect with a bichromate battery. If I close the circuit, both rods exhibit *magnetization*; but while the soft iron rod (e, fig. 103) can support a long chain of pieces of iron, on the steel one (s) I can only hang *one* piece; the second falls. Yes—now it clings to it! After a little time I can add another piece of iron; still the lifting power of the steel rod is considerably smaller than that of the soft iron rod. Now I cut off the current—from the iron rod all the pieces except one fall immediately, but from the steel not one.

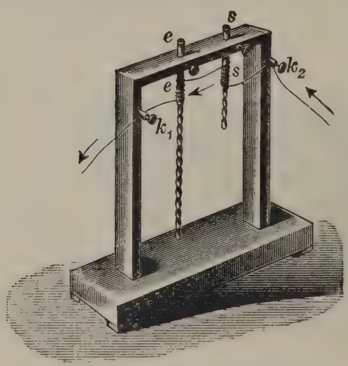


Fig. 103.

I take away the pieces of iron from both rods and again present them to the poles: the steel rod has

preserved its magnetic force, but the iron appears to have become entirely demagnetized. We will now repeat the experiment, but first stick bits of thin paper on the poles of both rods. Both exhibit a somewhat smaller lifting force than before, and, when the current is switched off, all the pieces fall away from the iron, while all remain clinging to the steel rod: that is to say, soft iron becomes strongly magnetized when encircled by an electric current, but only for such time as the current acts; but the steel keeps its magnetism in a great measure.

Magnets formed of soft iron core surrounded by

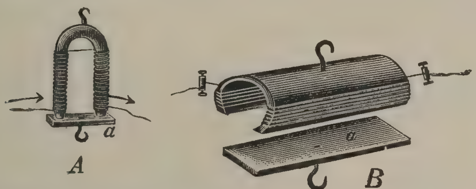


FIG. 104.—A, horse-shoe electro-magnet; B, Joule's electro-magnet, $\frac{1}{10}$ natural size.

an electric current are called electro-magnets. Their portative strength increases from the beginning with the number of galvanic cells arranged in parallel, and surpasses that of all other magnets. As in the case of steel magnets, their effect is strengthened if both poles are connected by what is called the *armature* or keeper. In fig. 104 we see two types of these horse-shoe electro-magnets. One of them, B, has very broad poles, which are very close to each other, and exhibits—as it consists also of very soft unannealed iron—although it has only five turns of strong copper wire, a very remarkable *lifting power.* The specimen before you weighs only 890 grammes. Let us test its strength. I switch on the current of a

large bichromate cell. Try to pull away the keeper. Scarcely anyone of you can do it. Now I connect with it another cell. Two of you can scarcely do it. An experiment, done out of class, showed that this little electro-magnet has a lifting power of more than 120 kg., *i.e.* it can lift more than 100 times its own weight. Thus you see what gigantic dynamic action our unlikely looking source of electricity can call into being, and you will therefore understand why electro-magnets play such an important part in practical life. But of this more later. I will merely mention now that with the assistance of larger electro-magnets it can be proved that bodies possess magnetic qualities, which under normal circumstances exhibit an entire absence of such property, and, therefore, for a long time, were considered entirely non-magnetic, as, for example, wood, glass, etc. (Appendix, 23, p. 397.)

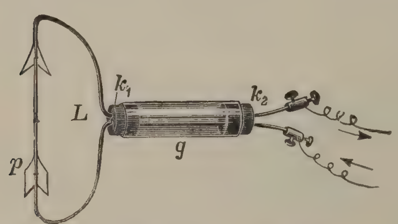


FIG. 105.—Conductor for experiments on the deflection of the magnetic needle by the electric current, ⅓ natural size.

We have seen that a magnet exercises a directing force upon a conductor, through which flows an electric current. Must not, therefore, an electric current exercise a like influence upon a movable magnetic needle? We have already observed that a solenoid can cause the magnetic needle to deflect, but in this case may not the spiral form of the conductor have some bearing upon the fact?

I take a tube of strong glass (*g*, fig. 105), fitted with good corks at each end. I then bend a piece

of strong silk-covered copper wire, in the shape shown in the figure, and push the ends through the first cork (k_1), and then, leading them along the tube, put them through the other cork (k_2), and fasten the ends with the electrodes of a cell by binding screws, so that the current flows through the loop in the direction of the cardboard arrow (previously fixed on it). Holding this conductor with the arrow pointing upwards, I present it to the south pole of a magnet pointing away from you (A, fig. 106). The needle is deflected, and turns its north-seeking pole (marked by a red paper) to the west. Then, without altering the direction of the

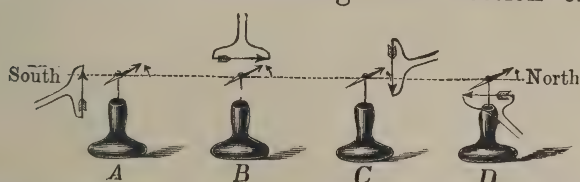


FIG. 106.—Deflection of the magnet needle by the galvanic current.

current, I move the conductor round the needle in the same vertical plane—the deflection remains the same. I repeat the experiment, but hold the wire loop in such a manner that the arrow, and of course the current too, has the opposite direction—the north-seeking pole is now, in all positions of the conductor, deflected towards the east, while before it always pointed west.

As a check experiment, I hold (A, fig. 107) the wire loop so that its plane has a north and south position and the circuit, now closed, surrounds the whole needle, and, in fact, flows over the needle to the north. You see that the north-seeking pole, as in the last experiment, remains deflected to the west; but if I turn the

loop 180°, I cause the stream to flow *through the needle* to the south, and thus the *north pole* turns *east* (B, fig. 107). We can therefore express the law as to all the cases of direction observed by us as follows:—*Let us imagine ourselves swimming forward with the current, our face turned to the magnetic needle; then the north-seeking pole is deflected to the* left (Ampère).

Ampère's swimming rule.

This rule, which is of great importance, as you will learn later, for the deflection of the magnet needle by the magnetic current, was discovered at the beginning

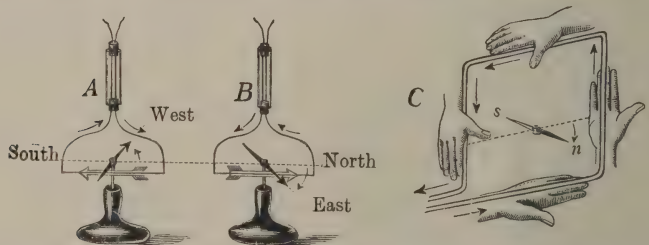


Fig. 107.—Ampère's law. A and B, $\frac{1}{10}$ natural size; C, the "Hand rule."

of the nineteenth century (before 1804) by Romanosi,[1] and later, in 1820, by the Danish physicist Oersted. The law of deflection we owe to the Frenchman Ampère, and in his honour it has been called *Ampère's swimming rule.* Perhaps the following way of putting it is simpler than his: *If the palm of the right hand be turned to the magnetic needle, so that the tips of the fingers show the direction of the positive current, then the outstretched thumb will indicate the direction*

Hand rule.

[1] Oersted is usually credited with the discovery of the deflection of the magnetic needle by the electric current, as he published his observations, whilst Romanosi did not make his known at the time; at least they are only incidentally mentioned by a contemporary. (*Cf.* Appendix, 29, p. 401.)

in which the north-seeking pole will be deflected (Hand rule, C, fig. 107).

From the deflection of the magnetic needle we can also determine the direction of the electric current. This will be of use to us later on.

Law of the direction of the current.

If we place the right hand in such a position on the deflecting current that the palm is turned towards the magnetic needle, and the outstretched thumb points to the direction of the deflected north-seeking pole, then the positive current flows from the wrist in the direction of the finger-tips (*cf.* C, fig. 107).

Let us now collect all our observations, so as to take them in at a glance :—

(1) Electric currents flowing in the same direction attract each other; those flowing in opposite directions repel. *Movable conductors strive to place themselves in such a position that currents flowing in the same direction are parallel to one another.*

(2) *Spiral or corkscrew-shaped movable conductors (solenoids) exhibit a magnetic directing power*, and are attracted and repelled by a magnetized rod brought near them, just as is a magnetic needle.

(3) An electric current deflects, according to fixed rules, a magnetic needle brought near it, and induces strong magnetism in a piece of iron which it surrounds. Then *the north pole of the electro-magnet is at that end where the current flows in a direction opposite to that taken by the hands of a clock.*

How shall we explain the connection between magnets and the electric currents?

Weber and Ampère's hypothesis.

Weber and Ampère, the gifted discoverers of the laws of electro-magnetism, supposed each molecule of a magnet to be surrounded by an independent

electric current acting upon itself, and that a part of these "molecular currents," as the result of the magnetizing action of stroking with a strong magnet, acquire a position pointing in the same direction and parallel with each other (A, fig. 108). Thus these molecular magnets act with the same intensifying force upon each other as did the steel filings (p. 172). To magnetize is, therefore, to place the molecules so that they may be parallel with each other, and point in the same direction.

The unattainable limit of the magnetization of a body would be reached so soon as *all* the molecular

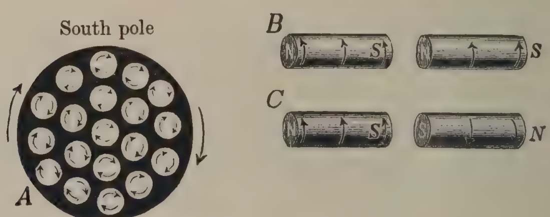


FIG. 108.—Direction of Ampère's molecular currents.

currents were turned in the same direction and parallel to each other. The different behaviour of iron and steel, when magnetized (p. 169), depends upon the fact that the molecules of iron are more mobile than those of steel. Hence the latter show a greater opposition to the directing force, but persist longer in the position when once attained. The iron molecules, on the contrary, return to their usual position immediately the outside force acting upon them is removed, whereby the molecular currents assume all kinds of positions, and their external action is abolished so that the iron appears un-magnetic (Weber).

This hypothesis of Weber and Ampère with regard

to magnetism[1] explains in the most natural manner the observed laws of magnetic attraction between unlike poles and the repulsion between like poles; for in the first case (B, fig. 108) the currents in the polar surfaces, having their opposite poles near each other, are pointed in the same direction and parallel, while, in the second case (C, fig. 108), where the neighbouring poles are like, the currents are opposed. This mutual attraction between electric currents and magnets follows as a necessary result of the directing force which two electric currents exercise upon each other. If, then, like Ampère, we look upon the whole earth-sphere as a large magnet, the north-seeking pole of which lies to the south, then the earth currents flow from east to west and therefore with the sun.

Directing force of the earth currents.

The simplicity of Ampère's hypothesis is fascinating, but on nearer acquaintance many difficulties appear. What, for instance, is the origin of these *continuous* molecular currents of iron and steel, and how are they kept constant? We must consider the theory of molecular currents only in the light of an ingenious conjecture, and refer the magnetic and electro-dynamic phenomena to a common cause. In the meantime it will furnish us with an excellent means of ascertaining our bearings. Let us imagine, for example, a vertically upright and strongly magnetized steel rod (M in A, fig. 109), the north-seeking pole of which is directed towards the upper end; then the surrounding space, so far as the magnetic action at a distance extends, is the magnetic field of the magnet.

[1] This hypothesis was first promulgated by Weber, but it is nearly always called Ampère's.

If now we bring near and parallel to the magnetized rod a very pliant conductor, in the shape of a loosely suspended riband, then the current running through it will show a tendency to take a position in the same direction and parallel to the molecular currents in the rod, and hence the conductor will wind itself round and round the magnetic rod. This we can prove.

Two thick wire rods (d_1 and d_3) are tightly screwed

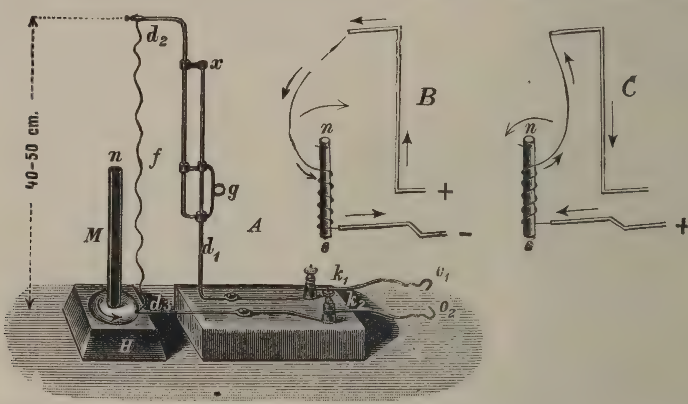


FIG. 109.—Lodge's experiment on the effect of a magnet upon a movable current conductor, modified; $\frac{1}{10}$ natural size (d_2, can be pushed up; g, handle).

into a small slab of wood 3 cm. thick (A, fig. 109). One wire (d_1) may be lengthened by pushing up the movable part (d_2). The free ends of d_2 and d_3 have small nicks about 8 mm. deep cut in them with a saw, and in these are inserted two or three lametta threads,[1] the ends being bound together with fine copper wire. The length of this riband (f) is about 35 cm. From the terminals (k_1 and k_2) on the stand

[1] See Appendix, 27, p. 401. What is here called tinsel riband is meant.—*Ed.*

run flexible wires, the ends (o_1 o_2) of which are connected with the commutator. The indicator is set to show the direction of the current in the riband (f). I now place the magnetic rod (M), fixed in a wood block (H), quite close to the loosely hanging conductor, and switch on the current. Immediately the metal thread winds itself round the magnet like the threads of a screw (B, fig. 109). Now I alter the current—the thread untwines, describes a large curve, and then again twines itself round the magnet, but in the opposite direction (C, fig. 109). By manipulating the wire rod (d_2), I can decrease, at will, the tension of the riband, so that only five turns are described round the magnet. If you remember that (in the experiment in fig. 96) the direction of the current is marked by the indicator of the commutator, you will easily understand that the riband always winds itself round the magnetic rod with its north pole directed upwards, so that the current in the riband (seen from above) encircles the rod in a direction opposite to that in which the hands of a clock move; and *vice versa* if I turn the rod and the south pole is directed upwards. In both cases, as a matter of fact, the flexible conductor always assumes such a position that the current flows in the same direction, and is parallel to the hypothetical molecular currents.

This reciprocal action between magnets and electric current thus observed gives us an inkling—in the light of Ampère's hypothesis—of the connection between magnetic and electric phenomena. The deflection of the magnetic needle further offers us a means of showing the presence of the weakest electric currents.

Apparatus of this kind are termed current-finders or *galvanoscopes.*

The Ampère's parallelogram already used by us (fig. 110) can do us good service in this case. In place of the mercury contact cup I put [see B] a small glass tube (g) with a narrow cylindrical aperture. To

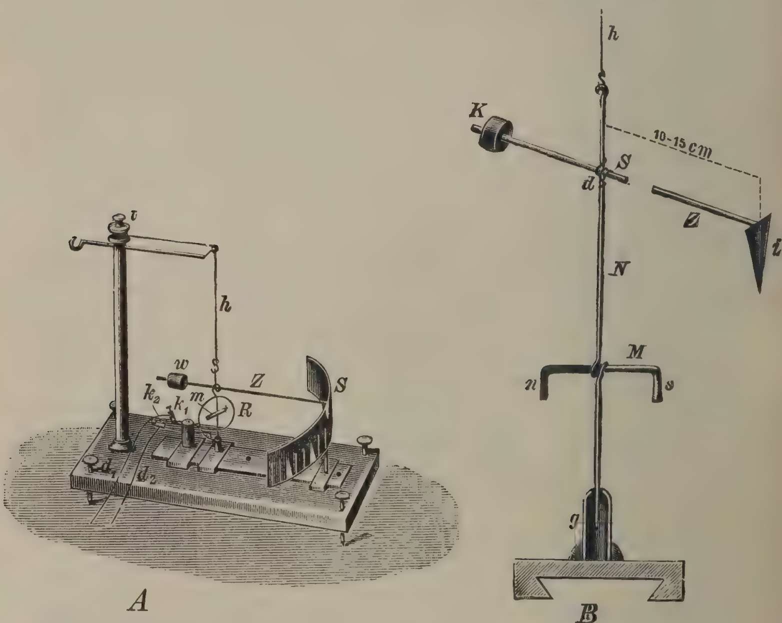


FIG. 110. — A, Ampère's parallelogram as galvanoscope, $\frac{1}{10}$ natural size; Z, straw indicator with paper pointer (p) and counterweight (w) of cork; S, rough scale (a piece of sheet-zinc covered with paper); B, suitable form of the magnet (M), $\frac{2}{3}$ natural size.

the hair (h) I hook an aluminium wire (N), which carries a short magnet (M), made out of a piece of magnetized knitting needle. At the upper end of the aluminium wire a straw (Z) is fastened to act as indicator; the lower end of the wire dips into the glass tube, by which contrivance a to and fro motion of the magnet is avoided. Round the magnet a ring of strong

copper wire is so fixed that the magnet occupies the centre of the circle [see A]. I now push the paper scale (S) to the right distance and turn the whole instrument so that the magnet swings in its ring. From the east of the apparatus, you can easily follow the deviation of the magnetic needle by the movement of the paper pointer (i).

You will remember how difficult it was to prove the presence of free + E and − E at the poles of a cell, since the sensitive aluminium electrometer gave no divergence when directly touched, and only when the condenser was employed did a weak charge manifest itself.

Now I employ a small zinc and carbon cell in the same manner as we recently used it (*cf.* fig. 92, p. 207). Scarcely do I touch the terminals (k_1 and k_2, fig. 110) with the electrodes of the cell, than the needle swings quickly aside, sways to and fro, and at last places itself at right angles to the plane of the wire, while the indicator travels along the scale.

Now observe the indicator. I slowly lift the zinc rod out of the fluid. Look! the angle of deflection of the magnetic needle decreases in proportion as the part of the zinc and carbon rods in the solution becomes smaller. Now, when the two rods are only just touching the fluid, the divergence scarcely shows three scale divisions (S, fig. 110, A) and it is therefore very small. A check experiment with the electrometer gives the same amount of divergence, no matter whether the rods just touch the fluid or are entirely immersed. What does this signify? We know that the electrometer measures the difference of the degree of electrification of the free poles of a cell,

as also the electromotive force of the cell (see p. 196). Can it be that the deflection of the magnetic needle on the galvanoscope has another meaning and is therefore not dependent on the electromotive force?

Our intention was to use the galvanoscope as a current-finder, and compare its sensitiveness with that of the electrometer; but as we have encountered varying readings in the two instruments, we must study the meaning of the readings of the galvanoscope. First I must draw your attention to a means which will allow us when necessary to increase greatly its sensitiveness.

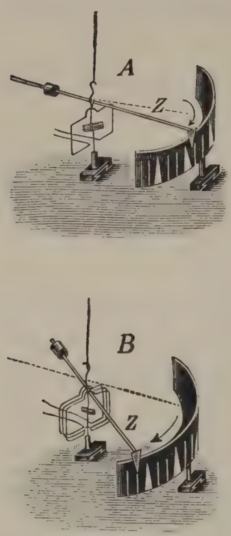


FIG. 111, A and B.—Influence of the number of windings on the extent of the deviation, $\frac{1}{10}$ natural size; A, single coil; B, coil with ten windings (only three are shown).

I again lift the zinc rod out of the fluid until it only just touches it, and the divergence is very small. Now I place inside the first coil another one (A, fig. 111), which is smaller and, therefore, nearer to the magnetic needle—the divergence is already a little greater. Then I put in its place a frame (B, fig. 111) consisting of ten windings of silk-covered copper wire (in the fig. only three are visible), and the divergence increases considerably. In short, the divergence increases in proportion to the number of turns of wire: that is to say, if the electric current is carried round the magnetic needle many times, then the deviation is multiplied; hence an apparatus of this kind is called a multiplier (Schweigger, 1821).

Just as the deflection of the magnet needle by the electric current was used for the construction of a galvanoscope, so also the deviation of a solenoid by a magnet (p. 224) may serve the same purpose. According to this principle, first enunciated by d'Arsonval, the best measuring instruments used in practical work are now constructed. As, however, these solenoid galvanometers (called also by some firms

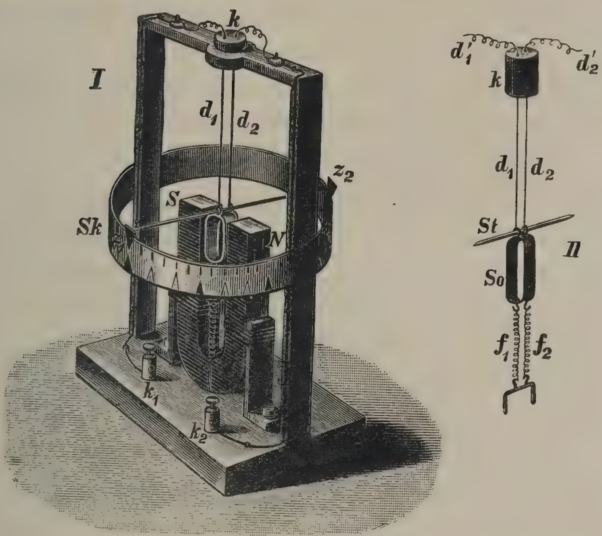


FIG. 111, C.—Working model of a solenoid galvanometer, $\frac{1}{5}$ natural size.

rotary coil galvanometers) are very carelessly constructed, we will endeavour to explain the principle of it by means of an easily arranged model.

Here (fig. 111, C) we have a horse-shoe magnet, consisting of three plates. It is fastened to the wooden block so that the poles point upwards. The distance between the legs is 30 mm. Between these hangs the solenoid, of 100 windings of fine silk-covered copper wire (0·15 mm. thick). The apparatus

is still more effective if a fixed cylinder of soft iron is fitted inside the solenoid, without touching it (*cf.* fig. 131, p. 289). The wires of the solenoid are introduced through a cork (k) fitting tightly in the upper frame and able to turn in it. By this means both the height and the position of the solenoid can be regulated. On the wooden pin (II, *st*), pointed at both ends, the indicators (Z_1 Z_2) are fitted. These are made of a straw or a tube of aluminium, 120 mm. long, carrying at the end paper arrows.

To keep this solenoid vertical, two hair springs of nickel (f_1 f_2) are fastened to it. (These may be replaced by a single spring or an unstretched rubber band.) Contact is made by the binding screws (k_1 k_2), which are joined by strong wires with the fine wires of the solenoid. The circular scale may be easily raised or lowered (the indicator must be partially pulled through the loops and one end then turned upwards), so that the solenoid may always be visible. By cutting through the cork, the distance between the wires (10 mm.) may be changed or their position adjusted, and the changing of the solenoid facilitated.

If we allow the current of one of our small cells (fig. 92, p. 207) to flow through the terminals, the indicator is greatly deflected according to the direction of the current to the right or left. The elasticity of the two suspension wires (called the "bifilar suspension") strives to turn the solenoid back to its position of rest. It therefore stops at a point more or less remote in proportion to the strength of the two forces. The stronger the current the greater the deflection, as in the case of the magnetic needle.

The great advantage of the *solenoid galvanometer*

consists in the fact that it is not necessary to place it in the magnetic meridian.

Before we leave this part of the subject, I should like to show you, for the sake of comparison, the magnetization effect of the current generated by the influence machine.

I wrap closely round each of two similar horseshoe magnets ten turns of strong copper wire, covered with gutta percha. I screw both magnets between two pieces of ebonite in a vertical position in two stands. Through one of the wires I pass the current of a bichromate cell, and through the other that of an influence machine, which gives a spark of 2 to 3 m. without the Leyden jars.

The electro-magnet of the cell exhibits a lifting power of 8 kg.; that of the influence machine scarcely $\frac{1}{50}$ kg. Yet this magnet, together with its keeper, and a scale pan of paste-board, and the necessary weights, weigh only 20 grammes. Hence you see that—with regard to the dynamic effect—the bichromate cell is far superior to the influence machine.

Our present object is attained. We shall next try to solve the riddle which confronts us in the diversity of the *data* yielded by the *electrometer* and the *galvanoscope*.

CHAPTER IV

Graduation of the galvanoscope. Construction of a scale. Effect of arrangement in series and in parallel with short and long conducting wires respectively, and with insertion of liquid resistance or current damper. Meaning of current intensity. Comparison of electro-dynamic and hydro-dynamic phenomena. Deduction of Ohm's law, and the best arrangement of the cells of a battery. Specific conductivity and electric-resistance. Practical unit of resistance, the ohm. Table of electric conductivities and resistance of different metals. Influence of resistance of a wire on heating by the electric current. Demonstration of the comparative resistance of wires by six-fold manometer, and by Lenz and Looser's method. Determination of internal resistance of element or battery. Current intensity in branch conductors. Measurement of great intensities. The solenoid galvanometer as voltmeter and as ampèremeter. Measurement of resistance by Wheatstone's bridge.

In a former chapter we gained a knowledge of some of the effects of the closed galvanic circuit flowing continuously through the conducting wire, and we compared the processes going on in it with those before observed in the conducting rods of an influence machine working intermittently. Further experiments taught us a number of new dynamic actions.

Retrospect.

Let us thus summarize the result of these studies:—

(1) If the current of a battery of constant cells arranged in series, traverses a very fine and long wire of as uniform a thickness as possible, the fall

of the current in the conductor is constant: that is to say, every two equidistant points of the conductor have the same difference of electric level.

(2) Electric currents flowing in the same direction are attracted to each other, those opposed to each other are repelled; therefore movable conductors show a tendency to place themselves in the same direction as, and parallel to, one another. If the current is strong enough, a movable suspended circular or spiral conductor or solenoid, when merely acted on by the earth's magnetism, takes up such a position that the current seen from the south flows from above to the east, *i.e.* clock-wise.

(3) A piece of iron encircled by the electric current becomes a strong magnet (electro-magnet) while the current is in operation. Magnets and movable current conductors exercise upon each other such a directing force that the electric current and Ampère's hypothetical molecular currents arrange themselves in the same direction and parallel to one another. The molecular currents of a magnet revolve round it—if one looks towards the south-seeking pole—clock-wise; accordingly the magnetic currents of the earth must have a direction from east to west.

With regard to the deflection of the magnetic needle, the following rule has been deduced: If the right hand, with the palm turned towards the magnetic needle, is held to the deflecting part of the current conductor, so that the electric current appears to flow from the wrist to the finger points, then the outstretched thumb indicates the direction of the deflected north-seeking pole.

Hence we easily get this rule for the direction of the current:

If we place the right hand on the deflecting part of the current conductor, so that the palm of the hand is turned towards the magnetic needle and the outstretched thumb marks the direction of the deflected north-seeking pole, then the electric current flows from the wrist to the finger tips.

Our next task is to go more closely into the results given by the galvanoscope.

When we were engaged in quantitatively comparing the phenomena of static electricity (p. 30), our first endeavour was to graduate or calibrate empirically a sensitive electroscope, by carrying to it repeated and equal charges of electricity, so as to determine according to our arbitrarily chosen unit of electrification the strength of the charge from the divergence of the leaf of the electrometer. By this means, out of the electroscope a very serviceable electrometer was evolved. Shall we not in the same manner be able to calibrate the *galvanoscope* and thus obtain a *galvanometer*.

Since our Ampère parallelogram is not very convenient, we will use a galvanoscope constructed particularly for demonstration purposes (fig. 112). A movable upright support (S) stands on three adjustable feet, carrying a box-compass with short magnetic needle resting on a steel point. The magnetic needle bears at right angles to its magnetic axis two long aluminium indicators, whose ends, terminating in coloured paper, travel round a scale fixed on the upright side of the circular

compass case. It can thus be easily seen by you from the side.

As the conductor of the deflecting current there is a strong copper ring (R), which turns on its horizontal axis. The ends of the ring, which do not touch the compass case, are fitted with binding screws (K_1 K_2). The sight (V), fixed on the foot of the stand, is used to obtain an accurate reading of the scale, and, at the same time, to show any chance movement of the stand itself.

To render the scale divisions more visible from a distance, the degrees 0°, 10°, 20°, are indicated by triangles, the 0°, 30°, 60°, 90°, being coloured red; the others black (G, fig. 115) [*cf.* Appendix, 31, p. 402].

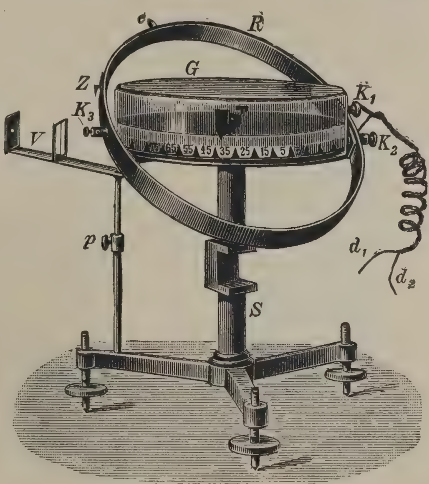


FIG. 112.—Demonstration galvanometer, ⅐ natural size. (Sine and tangent compass.)

Now I adjust the box so that the fixed sight (V) is exactly opposite 0°; then I slowly move the whole apparatus, together with the table, until both indicators are at zero, and place the copper ring R in a vertical position. I connect the binding screws by flexible silk-covered wire with the commutator, and this latter instrument with a very constant cell, for instance with our Daniell's U-shaped standard cell (fig. 92, p. 207), or with Fleeming's cell, which you see here (fig. 113). The chemically pure or well-amalga- Standard Daniell cell, after Fleeming.

mated zinc element dips into a solution of sulphate of zinc, and the copper into a solution of sulphate of copper: 1 and 2 are stop-cocks for adding quantities of fresh fluid, while by 3 those already used up flow away. By this contrivance an extremely constant source of current is obtained, and the fourth stop-cock (4) serves to empty the apparatus. I close the current—the divergence is, when the needle has come to rest, 12·5°. Now I slowly press down the copper ring (R, fig. 112). The divergence decreases gradually and at last becomes zero, when the ring is horizontal. We are, therefore, able to make the divergence large or small, as we like, for the range between 0 and 12·5°. Let us choose 10°—now by means of the clamping screw K_3 (fig. 112), I fix the ring in that position, and then reverse the current. The indicators turn to the other side and remain there at 9·8°.[1] Evidently the straight lines joining the two indicators are not quite perpendicular to the magnetic axis of the needle; still, that does not matter; we need only note the deviations for both directions of the current and take the *mean* of both readings. If the two indicators do not work accurately enough on equal divisions of the graduated scale, we must take for the one direction of current two readings, a_1 and a_1', and for the other a_2 and a_2'. Then the true value of the

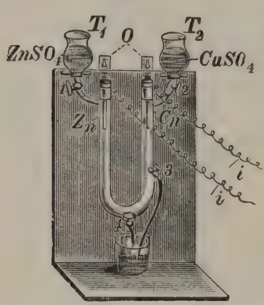


FIG. 113.—Fleeming's standard Daniell cell for graduating the galvanometer, $\frac{1}{5}$ natural size.

[1] The wires leading to the galvanometer (fig. 112) are twisted together, to prevent any deviating movement on their part.

angle of deflection is the mean of the four readings, so that $\alpha = \frac{(\alpha_1 + \alpha_1' + \alpha_2 + \alpha_2')}{4}$.

Now we can proceed to the graduation of the galvanoscope. As the unit of galvanoscopic current effect, we will take that yielded by our standard Daniell cell.[1] We have now merely to arrange the experiment so that the needle, without current, has the same deflection as with the cell; therefore when a fresh current traverses it, the galvanoscopic action

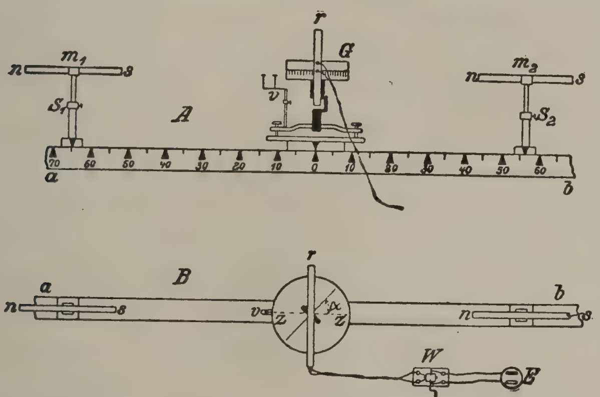


FIG. 114.—Graduation of a galvanoscope by two magnets in the east-west position, $\frac{1}{20}$ natural size. A, side view; B, view from above.

is added to the former, and consequently is doubled, or the third time is triplicated, and so on.

I place the galvanoscope (G, fig. 114) on the lower bar of the optical bench (ab), exactly over the

[1] The closer the glass or asbestos wool in the U-shaped tube is packed, or the farther the rods are lifted out of the fluid, the weaker, with equal polar difference, is the electric current. The cause of this we shall know later on as "internal resistance." This regulating contrivance renders this cell especially convenient for the experiments which follow, when the galvanoscope is not fitted with a rotating ring and a resistance or rheostat.

zero point of the millimetre scale. Now I give the optical bench an east to west direction: that is to say, such a one that the aluminium indicators (z z, fig. 115, B) are parallel to it, and I turn the compass in such a manner that the indicators and the fixed sight V point exactly to 0. I close the circuit, and the divergence is 10°. Now I break the current, and place two long magnetized rods (m_1 m_2) on suitable stands (s_1 s_2) and bring them gradually near, until the same deflection $a_1' = 10°$ is attained. Then I close the circuit, giving it the same direction as you perceive is given by the indicator of the commutator. The second deflection $a_2' = 19{\cdot}8°$. In a similar way we get $a_3' = 27{\cdot}9$; $a_4' = 35{\cdot}1$; $a_5' = 41{\cdot}5$, etc. You notice, then, the spaces between the scale degrees become constantly smaller: that is to say, the deflections of the galvanoscope are not proportional to the deviating action of the current, any more than was the case with the electrometer.

In this way we graduate the galvanoscope until nearly 70° from zero point is reached, when the increase is too small to note and we leave off. Now we repeat the whole measurement with the reversed current, so that the needle deflects in the contrary direction. Let us now denote the deflections by a_1'' a_2'' a_3''—then we get the true deflection, if we take the mean of the corresponding deflection of both current directions, *e.g.*,

$$a_1 = \frac{(a_1' + a_1'')}{2}\,;\ a_2 = \frac{(a_2' + a_2'')}{2}, \text{ etc.}$$

It now only remains to mark suitably the scale points obtained during the graduation, to get a graduated scale, which will perform the same services in the case

of the galvanoscope, as the scale of the electrometer did for that instrument (Appendix, 31, p. 402).

From an previous series of experiments I obtained as a mean out of five measurements :—

$l =$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$a =$	7·5	14·7	21·5	27·8	33·4	38·3	42·7	46·5	49·8	52·7	55·4	57·7	59·8	61·5	63·1	64·5	65·9	67·1	68·2	69·2

Graduated scale of the galvanometer.

To trace the scale for our galvanoscope, I next remove the glass cover of the compass and the needle, lift off the ring with the scale of degrees, and stretch tightly round it a strip of drawing paper 12 mm. broad. As this ring is 30 mm. deep, the entire scale

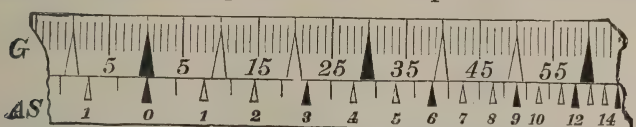


Fig. 115.—Specimen of the graduation scale (AS) of the galvanometer on the vertical scale of degrees (G), so arranged that this remains visible, ½ natural size.

of degrees is visible above the paper strip, as are also the points of the triangles. I can therefore easily mark on the strip of paper the proper points of the graduation scale (fig. 115, AS). But as drawing the scale would require too much time, because it must be drawn on both sides and from both zero points (in all therefore four times), I prefer to fasten on the strip a scale already completed after very careful measurements. Before I fix the ends of the paper strip with some adhesive, I must convince myself that the zero points of both scales agree.

We can now use either the scale of degrees or the graduation scale at will, but for the present the latter will serve. Thus our galvanoscope has become a

measuring instrument, which we shall call our galvanometer, although by its means we are only able to measure the deflecting action of the galvanic current (Appendix, 31, III, p. 403). In what relation does this action of the current stand to the size or to the grouping of the cells? To discover this is now our task.

Here are three immersion cells, one of which is

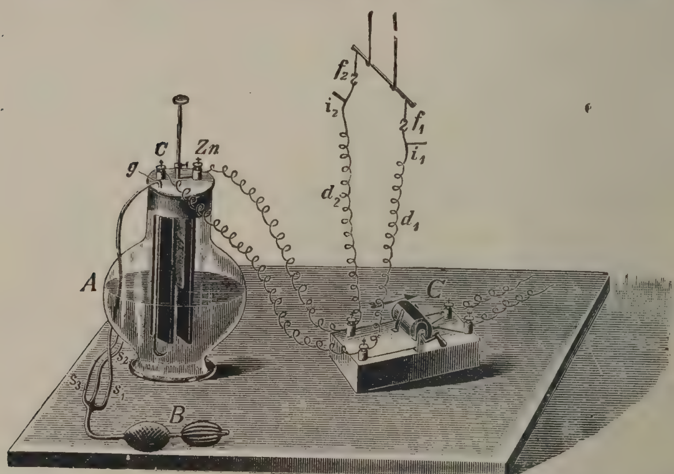


FIG. 116.—Immersion cell (with inflation ball (B) fitted with triple glass tube for three cells). The extra wires, d_1 d_2, to the commutator (C), are for electrometer measurements, and are usually suspended for insulation.

reproduced in fig. 116. Two carbon plates are connected to each other by the binding screw C, and dip into a solution of bichromate of potash mixed with sulphuric acid, whilst the smaller zinc plate may be more or less immersed at will by moving the brass rod fastened to it, or it may be entirely removed, which of course stops the current.[1]

[1] Still better are the new immersion cells with two zinc and three carbon plates, which are let down together, and when not

The tube in the middle of the cover is electrically connected with the other binding screw (Zn). Through the ebonite cover a glass tube is introduced, which ends in a fine point beneath the carbon plates, and through which air is blown by the bellows (B) to keep away hydrogen from the carbon plates, when the circuit is closed. Thus, the otherwise rather inconstant element is made very constant, which we can judge by the fact that the deflection of the needle of the galvanometer, when put in the circuit, steadily declines, while when the blowing is kept up, it remains unchanged.

We will now and later, as a check, determine the electromotive force by the electrometer. With this object I fix to the terminals of the commutator (C, fig. 116), which are connected with the electrodes of the element, two fine additional wires (d_1 d_2), provided with insulated handles of sealing-wax (i_1 i_2). After the current through the commutator is interrupted, I carry these to the condenser plates of the electrometer. When not in use, I hook them to rings, hanging from the ceiling by silk threads (f_1 f_2).

We get, on the electrometer, for the three cells (the zinc plates just dipping in the solution), I = 1·8; II = 2·0; III = 1·9 volts. Now I turn the commutator, so that the circuit is closed, and therefore the current flows through the *galvanometer*—the deflection is three degrees on the graduated scale, if the copper ring of the compass is vertical. By lowering the ring I diminish the deflection until it is exactly

in use may be lifted out entirely; but we must substitute pressure terminals for the binding screws with one aperture, and screw the two fly-nuts together (K, fig. 117, p. 252).

two degrees of the graduated scale.[1] Now I screw the ring fast and put in circuit the element II. The deflection is 2·8; somewhat larger. To make the deflections equal, it is only necessary to raise the zinc plate slowly—there, now, $a_2 = 2$ also. I do the same with the cell III. Now all three cells measured by the galvanometer are equally strong, but the electromotive force remains unchanged.

We can now begin measuring.

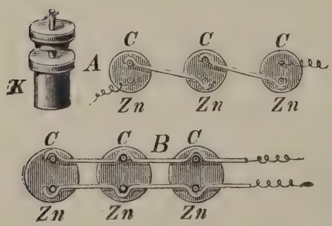


FIG. 117.—A, convenient arrangement in series; B, in parallel; K, a binding screw of the cell, ½ natural size. On K are two female screws, one above the other. In the figure the lower one is tightly fastened.

The element I gives, when the position of the commutator is as above, 2·0; when reversed, 1·8; therefore the mean = 1·9. The same is the case with the cells II and III.

Since our terminals (K, fig. 117) allow us to do so, we can arrange the cells, either (A) in series, or (B) in parallel, by connections of fine copper wire.

Action of short, thick conducting wires.

I have purposely arranged the deflections on the galvanometer so that the readings for one element in both this and the electrometer shall agree as far as possible, and thus their immediate comparison is feasible. Fig. 117 shows the arrangement for all the three cells.

Two cells, placed in series, give on the galvanometer, when between the two, 1·9: that is just the

[1] If the galvanometer ring is not adjustable, the rods must be taken out of the cell. In this case, when the action of the galvanometer has to be regulated, immersion cells are convenient, otherwise cupron cells (p. 210) are preferable.

same deflection as one cell. The same is the case with three cells; while, on the other hand, the divergence on the electrometer increases in proportion to the number of cells (see p. 206).

Now I arrange two cells in parallel.[1] The galvanometer marks 3·8, the electrometer 1·9. Therefore, on the galvanometer we get double the effect that we did with one cell. For three cells the deflection is 5·75; therefore three times as great. The following table will put the above clearly:—

I. Short and Thick Conducting Wires.

No. of Cells.	A. Galvanometer.		B. Electrometer.	
	Arrangement.		Arrangement.	
	Series.	Parallel.	Series.	Parallel.
1	1·9	$1·9 = a_1$	(1·9)	(1·9)
2	1·9	$3·8 = 2a_1$	3·8	1·9
3	1·9	$5·8 = 3a_1$ (almost)	5·6	1·9

A glance at this table shows us that the action of the current on the galvanometer is the opposite to that on the electrometer. While in the last-named case the electromotive force is in direct proportion to the number of cells arranged in series, the effect on the galvanometer, when the cells are arranged in parallel, is proportional to the number of the cells;

[1] For this we use flexible wires, about $1\frac{1}{2}$ mm. thick, of tinned copper, such as are employed for electric lighting purposes. With the help of the double binding screws the otherwise inconvenient parallel arrangement can easily be carried out.

but when the arrangement is in series, it remains the same. We have used short, thick conducting wires. It would be premature were we to determine the law of the action of the current from this one series of observations. We must rather take into account attendant circumstances. What influence, for example, have the conducting wires?

Influence of fine, long wires.

A portion of the long manganin wire which we have already made use of (p. 214) is inserted in the circuit before the commutator. The deflection on the galvanometer becomes immediately smaller; but on the electrometer the divergence is unchanged, and I am scarcely able, even by raising the compass ring, to bring the deflection for one cell up to the earlier height (1·9). We thus get the following table:—

II. Fine Manganin Wire (about 1 m.) put in Circuit (R, Fig. 94).

No. of Cells.	A. Galvanometer.		B. Electrometer.	
	In Series.	Parallel.	In Series.	Parallel.
1	1·9	1·9	1·9	1·9
2	3·5	2·2	3·8	1·9
3	4·9	2·7	5·7	1·85

We perceive immediately that the action of the current on the galvanometer is much weakened by the insertion of a fine wire, just as if we had taken the zinc plate partly out of the fluid, and had thereby diminished the contact surface. On the other hand, the electromotive force measured by the electrometer has remained unchanged. Table II. shows us,

further, that in the case of a short conductor, the proportion observed between the number of cells arranged in parallel, and the deflection on the graduated scale no longer holds; and that, when the arrangement is in series, the deflection increases.

It appears as if the thin wire, of 1 m. long, offered some resistance to the flow of the electricity, by which the action of the current on the galvanometer is damped; hence we name this action the *resistance* of the conductor. From static electricity we know that different bodies conduct electricity with varying Resistance.

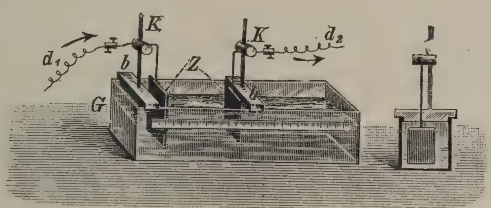


Fig. 118.—Current resistance, $\frac{1}{5}$ natural size. (Two movable amalgamated zinc plates in a concentrated solution of sulphate of zinc.) A paper mm. scale is fixed on the side of the glass.

degrees of ease, and we distinguish between good conductors (metals), bad conductors (wood, hemp, etc.), and non-conductors or insulators (amber, silk, ebonite, mica, etc.).

Shall we find that the conductivity of the wires depends on their length and thickness? This question is very important, but first we will endeavour to give a clear understanding of the indications of the galvanometer.

From side to side of this glass trough (G, fig. 118) two small bars of wood (b b) are placed and fitted with movable amalgamated zinc plates and binding screws (K K) for the conducting wires (d_1 d_2). I pour into

the water of the trough a solution of zinc sulphate ($ZnSO_4$) and put this column of liquid into the circuit instead of the German silver wire—the deflection is imperceptibly small. Now I push the right-hand plate slowly nearer—the deflection gradually increases, until the plates touch each other, when it goes up with a bound. The deflection in this case is just as great as in that of the short wire conductor (Table I.) alone. With the help of this resistance we have it in our power to weaken the current at will within certain limits.

Current dampers.

I move the zinc plates of the resistance so far away from each other that the deflection for one cell shows only 0·5 divisions of the graduated scale. When the direction of the current is reversed we get 0·4, or, taking the mean of these, $a_1 = 0{\cdot}45$. We will repeat the series as before, and tabulate results.

III.—A LIQUID RESISTANCE INTERPOLATED.

No. of Cells.	A. Galvanometer.		B. Electrometer (E.M.F).	
	Arrangement.		Arrangement.	
	In Series.	In Parallel.	In Series.	In Parallel.
1	$0{\cdot}45 = a_1$	0·45	$1{\cdot}9 = 1_1$	1·9
2	$0{\cdot}\ 9 = 2a_1$	0·45	$3{\cdot}8 = 2v_1$	1·9
3	$1{\cdot}34 = 3a_1$	0·46	$5{\cdot}8 = 3v_1$	1·9

We get exactly the same numbers, if we replace the liquid resistance (fig. 118) by a piece of our manganin wire 10 m. long (Fig. 94, R).

Hence we gather that the inclusion of the liquid resistance or a long, fine wire not only lowers the action of the galvanometer so far as the current is concerned, but also that the mode of action of the arrangement in series or in parallel is just the opposite of that (Table I.) in which only short, thick wires were the conductors: that is to say, the action of the current on the galvanometer, when a great resistance is put in the circuit, is proportional to the number of cells arranged in series, while the parallel arrangement does not affect it. The action of the current depends only on the electromotive force. This gives us a ready means of comparing the electromotive forces of the various cells by the aid of the galvanometer (*cf.* p. 290).

Intensity of current and resistance.

If, for the present, we call the cause of the action on the galvanometer the *intensity of the current*, and the cause of the damping action exerted in the liquid resistance, the *resistance*, then we may assume that at first (Table I.) we had a very small and now (Table III.) a very great resistance in the conductor. So we find:

(1) *The greater the resistance in the conductor, the less is the intensity of the current.*

(2) *When the resistance of the conductor is very small, the intensity of the current is proportional to the number of elements arranged in parallel; but, when the resistance is very great, it is proportional to the number arranged in series.* (In neither case has the mode of arrangement any influence on the intensity of the current.)

How are we to explain this contradiction? Evidently the electric current changes its character

according to the arrangement of cells. What, then, settles the intensity of the current or the effect on the galvanometer, as we called it at first for want of a more suitable expression?

We noticed that the electromotive force, or the potential difference at the free poles of the elements proportional to it, was quite independent of the magnitude of the immersed plates, or of the resistance in the conducting wires (at least within the limits observed by us), and only rested upon the nature of the metals and fluids employed.

Let us imagine the surfaces of the immersed plates divided into square millimetre spaces, and —speaking figuratively — an electric ray of equal (electromotive) force transmitted through each of these units of surface; then the sum of these "current rays" represents the entire quantity of electricity put in motion, *i.e.* the electric current itself. Of course it is quite immaterial how we group the "current rays," whether we derive them from one great plate, or from several small ones—that is to say, whether we use one large cell or several small ones the zinc and carbon plates of which are joined. When arranged in parallel, current rays of equal strength are added together; hence the quantity of electricity increases, while the fall of the current or electromotive force is unchanged. Perhaps this will become more clear to you, if you think of what takes place in a stream of water.

Hydrodynamic phenomena.

Imagine a horizontal circular canal (*cf.* fig. 80, p. 179), closed at one end by a tube containing a water-wheel which drives the water forward with a uniform force, so that a constant flow of water is

maintained in the canal. As we already know, a uniform fall of current is established: that is to say, the difference of level for equidistant points in the path of the current is constant. We observed the same thing in the electric current (p. 184).

What must we understand by *intensity of current*? Various replies may be given, according to the measure we employ. The simplest would be this: we ascertain the velocity of the flow, *i.e.* the distance traversed by the particles of water in *one* second, and measure the area of cross-section of the current; then the amount of water which flows through the section in one second is the required measure of the intensity of the current.

Intensity of current = quantity of water per second
= velocity × area of cross-section . . (1)

Meaning of intensity of current in streams of water.

This quantity of water, in volume, corresponds to a column of water, the height of which is the distance traversed by the stream in one second, and the base the area of the section of the stream. Instead of the volume, we could just as easily estimate the weight of the column of water. We should therefore have

Intensity of current = weight of water per second . . (2)

Similarly, we could measure the value (*i.e.* the energy) of the work of the current by determining the energy or power of work of a stream of equal velocity and 1 sq. cm. section. Then the product of the energy (already obtained) by the section of the stream (in sq. cm.) is a measure for the intensity of the current.

Intensity of current = energy of the stream
= energy per sq. cm. × sect. (in sq. cm.) (3)

I have purposely shown you, that in the case of the comparatively simple processes which a stream provided us with, the intensity of the current may be measured in various ways. You will, therefore, not be surprised if we make the acquaintance of other methods of measuring the intensity of the electric current than that already given.

What takes place if several canals, in which the water flows with equal fall, and therefore with the same velocity, are united in one stream? Evidently the fall or the velocity will remain unchanged, while, on the other hand, the cross-section of the stream has increased. The amount of water which flows through the main channel per second will be equal to the sum of the corresponding quantities of water in the several channels: that is to say, the intensity of the current will increase with the number of canals joined together, just as we noticed in the case of the galvanic cells in parallel, when we used short, thick wires which opposed no resistance to the flow of electricity.

If we allow the water to flow through *pipes* instead of in canals, then we have quite another state of affairs. If, for example, we bring water from an elevated reservoir through pipes to a low-lying place, then the pressure of the water flowing out (or the velocity of the stream) will depend only upon the *difference of levels*, and—leaving out the question of friction—will be quite independent of the length of the conducting pipes.

Let us call the force driving the water—it is just the same, whether this is called into being by a water wheel or by difference of level—"aquamotive force,"

then we have a new measure for the intensity of the current.

$$\text{Intensity of current} = \text{quantity of water} = k \times \text{aquamotive force} \times \text{cross-section} \quad . \quad . \quad . \quad . \quad (4)$$

Here k stands for a constant, depending on the masses employed, and it specifies the relationship between the aquamotive force and the velocity.

To give you an idea, though a rough one, of what happens when a great resistance stops the stream of water I will employ a simple arrangement (fig. 119). The bottom of a glass cylinder is cut away, and instead several layers of cotton-wool are stretched tightly across. I pour water into this vessel, until it is about 8 cm. high—and a few drops flow slowly out.

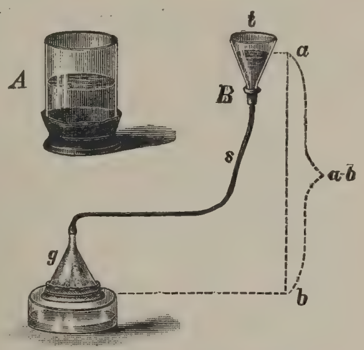


FIG. 119.—Action of a great resistance on the flow of water, $\frac{1}{10}$ natural size. A, difference if surface is small; B, difference if surface is great.

Another method of performing this experiment is shown in B, fig. 119. An inverted glass funnel is closed in the same manner as before, but is joined by a rubber tubing about 2 m. long (s) to another funnel (g). Into the top funnel I pour water and gradually lift it up—you see, as the water pressure increases, drops of water ooze out with greater frequency, and finally a thin continuous stream of water is established. In this case, therefore, the intensity of the current—if I may so express it—is no longer dependent on the cross-section of the column of water, but primarily on the water pressure, *i.e.* upon the difference of levels

$(a-b)$. You have here a case analogous to the arrangement of the cells in series, when a very great resistance is interpolated. . . .

Intensity. So far we have only observed the action of the electric current on the galvanometer. Properly, by the words *intensity of current* is understood the quantity of electricity which flows through a given section of the conductor in one second.

Intensity of current = quantity of electricity per second.

The expression "intensity of current" is not well chosen, for the word "intensity" embraces the meaning of energy, whilst "intensity of current" really implies the notion of quantity, and quantity of current = quantity of electricity per second. Nevertheless, the expression has taken root and is widely used.

Let us now examine what influence the electromotive force and the nature of the conductor has upon the intensity of the current.

From an experiment with the interpolated fluid resistance (fig. 118, p. 255) we saw that a column of liquid is a much stronger damper than a metallic conductor. Hence we can infer that "fluids are bad conductors of electricity," or that they oppose a greater resistance to the electric current than metals (wires). But the plates of the cells are separated by layers of fluids which also oppose a certain resistance, which we must take into calculation. I will, therefore, arrange an immersion cell, in which we can alter at will the space between the plates, and thus examine the effect of the distance between them.[1] Thus we

[1] The following experiment (figs. 120–122) is partly borrowed from Pfaundler, but much modified. Müller-Pouillet's *Lehrb. d. Phys.*, 9th (Pfaundler's) edition, Bd. iii. pp. 412–413.

shall be able to change the resistance in the conductor as well as in the cell itself, and note the effect on the galvanometer.

1. A glass trough (A, fig. 120) is two-thirds filled with a solution of bichromate of potash, with some sulphuric acid added. In it I place a pair of carbon and zinc plates, which are fastened to the little wooden cross-pieces, and may be raised as high as desired. The distance between the plates may be seen from the paper millimeter-scale gummed on to the side of the trough, and coated with melted paraffin (to protect it against any overflow of acid). Cell with variable internal resistance.

I connect the electrodes of the cell with the galvanometer (B, fig. 120), by two copper wires, each 1 m. in length (which I have cut from the same reel). The deflection is 4 degrees of graduation. Now I insert two longer wires of the same kind—the deflection ($a_2 = 3{\cdot}5$) is much less.

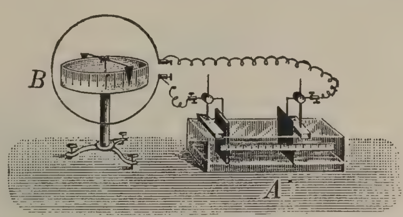


FIG. 120.—Relation between the external and internal resistance and the intensity of current. A, cell, $\frac{1}{10}$ natural size; B, galvanometer, $\frac{1}{8}$ natural size.

Now I move the plates further apart. You see the deflection diminishes greatly. An increase of resistance both in the cell and in the conductor decreases the intensity of the current.

If we name the resistance in the cell the "internal resistance" (w_i) and that of the conductor the "external resistance" (w_a), the sum of both resistances represents the entire resistance (W). External and internal resistance.

$$W = w_i + w_a.$$

What will result if we double the entire resistance?

II. I connect the galvanometer (G, fig. 121) by two wires, each 1 m. long, with the trough cell (E), and push the zinc plate closer to the carbon, so that the deflection is exactly 8 graduation units. This new position is marked by dotted lines, as are the wires also. The distance between the plates = 40 mm. The total resistance (in the cell, the conducting wire and galvanometer) let us take as 1, and we will also double each resistance. To do this, I insert between

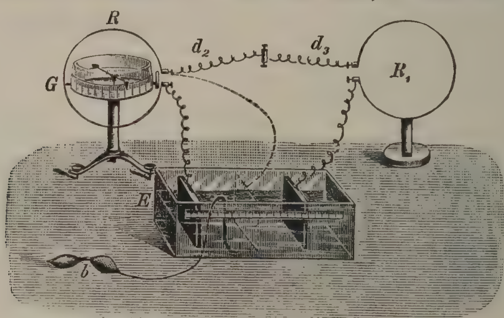


FIG. 121.—Dependence of the current intensity upon the total resistance. G, $\frac{1}{10}$; E, $\frac{1}{6}$ natural size. (The glass trough E has been drawn too broad. Its dimensions are $5 \times 5 \times 15$ cm.)

the galvanometer and the zinc plate two other similar wires, each 1 m. long, which are further joined by a strip of copper (R_1) of the same shape and measurements as the ring (R) of the galvanometer; therefore the external resistance is twice as great.

If I now move back the zinc plate to a point twice as far (2·40 = 80 mm.), then the total resistance is doubled and the deflection a_2 is between 3·9 and 4, therefore (almost exactly) half of the former. When the total resistance is doubled, the intensity of the current is half as great, or the current intensity is in inverse proportion to the total resistance.

III. We must now examine the influence of *the electromotive force.* In the middle of the glass trough I set up a wooden slab boiled in paraffin (H, fig. 122), with a rubber tube (g) round its edges, so that the trough is divided into two separate compartments. Close to the partition I place a carbon and zinc plate, and connect them by a short strip of metal, the resistance of which we must neglect.

Now I move the two end plates of the cells thus arranged in series so far away that the sum of their

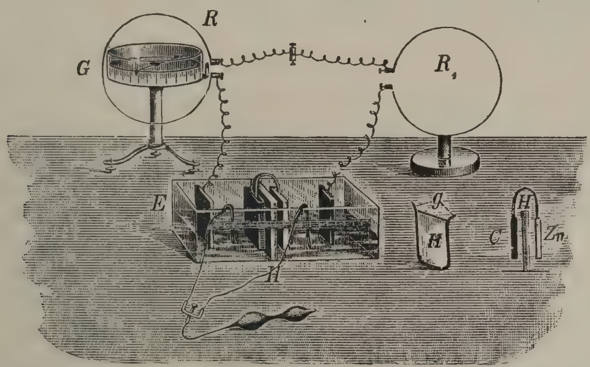


FIG. 122.—Dependence of the current intensity upon the electromotive force. G, $\frac{1}{10}$; E, $\frac{1}{8}$ natural size.

distances (80·8 mm.) is just the same as the distance between the plates in the last experiment. Now the total resistance is unchanged, but the electromotive force is doubled; the deflection ($a_3 = 7 \cdot 9$) is twice as great as before (3·95), or just as great as in a single cell with half the resistance. Hence we see

The current intensity is directly proportional to the electromotive force.

We can now state the entire law of current intensity.

The strength of the galvanic current is in direct Ohm's law.

proportion to the electromotive force (of the battery), *and in inverse proportion to the total resistance* (Ohm's law).

If we denote the required intensity of current by J, the electromotive force by E, and the total resistance by W, then the fraction $\frac{E}{W}$ will be proportional to the current intensity J. To make the value of this fraction equal to that of the intensity of the current, we must multiply it by a constant factor (k); then we get a measure for the intensity

$$J = k \times \frac{E}{W}.$$

Let us consider for the present, as the unit of current intensity (J), a current which will occasion on the calibrated galvanometer a deflection of 1 degree, and let us take the electromotive force of a Daniell's cell as unity; then, in general, the thrust which 1 Daniell gives is—according to the interpolated resistance—greater or smaller than 1. If now we choose such a wire as will give a thrust which = 1, then we can set down the total resistance w = 1, and use it as for the present an arbitrary unit of resistance. Then the fraction $\frac{E}{W}$ (where W is a known multiple of w) gives directly the current intensity, that is to say, we can so choose the unit of resistance that the above constant factor k = 1. Then it is clear that:

$$J = \frac{E}{W} \quad . \quad . \quad . \quad . \quad . \quad (I)$$

But since the total resistance (W) is composed of the internal resistance w_i, present in the cell itself, and the external resistance w_a of all the conductors

taken together; therefore $W = w_i + w_a$ (*cf* p. 263), and we get as a mathematical expression for the intensity of current:—

$$J = \frac{E}{w_i + w_a} \quad . \quad . \quad . \quad . \quad \text{(II)}$$

This law regarding the current intensity of galvanic cells, first discovered by the German scholar Ohm in 1827, furnishes, in its mathematical form, the key to the riddle—namely, as to how it is possible, when there is very little external resistance, for the intensity of the current to be proportional to the number of cells arranged in parallel, while, when the resistance is very great, it is proportional to the number arranged in series. At first this seeming paradox filled us with astonishment. At that time we had left out of our calculations, since we were dealing with very little resistance from the conductors, the fact that when the *parallel* arrangement was used (which is just the same as employing a cell with greater immersion plates) the internal resistance decreases, as does the number of cells, and therefore the intensity must rise. On the other hand, in the arrangement in series, when the current must overcome the internal resistance of each cell in turn, the internal resistance increases in the same ratio as the electromotive force; wherefore, when the resistance in the wire is a negligible quantity, the intensity does not change. The fall of the current, however, is now more powerful and better able to overcome a large external resistance, and therefore, in comparison with the parallel arrangement, the current intensity is greater.

This strikes us much more forcibly, if we imagine n number of cells, arranged first *in parallel*, and then

in series, and calculate the corresponding intensities for an infinitesimally small or for a very large external resistance.

I. *External resistance very small in comparison with the internal resistance* (*i.e.* $w_a=0$). For one cell the intensity is :—

$$J_1=\frac{E}{w_i+w_a}=\frac{E}{w_i+0}=\frac{E}{w_i} \quad . \quad . \quad . \quad (1)$$

(*a*) n Cells *in Parallel.*

Electromotive force as before $=E$

Internal resistance (n times less) $=\frac{w_i}{n}$

External resistance (vanishing) $w_a=0$

(*b*) n Cells *in Series.*

Electromotive force $=n\times E$

Internal resistance (n times greater) $=n\times w_i$

External resistance (vanishing) $w_a=0$

Intensity of Current.

$$\underset{n}{J}=\frac{E}{\frac{w_i}{n}+w_a}=\frac{E}{\frac{w_i}{n}+0}=\frac{E}{\frac{w_i}{n}}$$

or, if we multiply the number and denominator of the fraction by n, we get :

$$\underset{n}{J}=\frac{n\times E}{w_i}=n\left(\frac{E}{w_i}\right)=n\times J_1 \quad (2a)$$

$$\overset{n}{J}=\frac{n\times E}{n\times w_i+w_a}=\frac{n\times E}{n\times w_i+0}=\frac{n\times E}{n\times w_i}.$$

Here we strike n out,

$$\overset{n}{J}=\frac{E}{w_i}=J_1 \quad . \quad . \quad (2b)$$

i.e., when the external resistance is infinitesimally small the current intensity of the cells is increased when arranged *in parallel*, but NOT if arranged *in series.*

II. *The external resistance is so great that the internal resistance (even when the arrangement is in series) vanishes.* For one cell the intensity (when $w_i=0$) is :—

$$J'_1=\frac{E}{w_i+w_a}=\frac{E}{0+w_a}=\frac{E}{w_a} \quad . \quad . \quad . \quad (3)$$

(*c*) n Cells *in Parallel.*

Electromotive force $=E$

Internal resistance $=\frac{w_i}{n}$ (vanishing towards w_a).

External resistance $=w_a$

(*d*) n Cells *in Series.*

Electromotive force $=n\times E$

Internal resistance $=n\times w_i$ (very small in comparison with w_a).

External resistance $=w_a$

Current Intensity.

$$J'_n = \frac{E}{\frac{w_i}{n} + w_a} = \frac{E}{0 + w_a} = \frac{E}{w_a} = J'_1 \qquad \Big| \qquad \overset{n}{J'} = \frac{n \times E}{n \times w_i + w_a} = \frac{n \times E}{0 + w_a} = \frac{n \times E}{w_a} = n \times J'_1.$$

When the external resistance is very great in comparison with the internal, the current intensity is not changed when the elements are arranged in parallel. But when arranged in series, it is increased, but, for a particular external resistance (w_a), in no way proportionally to the number of cells; since, when the number of cells in series is very great, the internal resistance ($n \times w_i$) as compared to w_a can no longer be left out of calculation.

As you see, the theoretical result of Ohm's law is quite in agreement with our observations (pp. 252–257). What then appeared inconceivable, now appears as a necessary result of the dependence of the intensity of current upon the total resistance; whereas at first we only took into account the external resistance, *i.e.* that of the conductors. Let this be a caution to you, when commencing the study of a science, to give full consideration to all circumstances and side issues which may affect any of the phenomena observed.

Since any given number of galvanic cells may be arranged in different ways to form a battery (as, for example, fig. 123 for six cells), the question arises: How must the cells be arranged so as to yield the greatest possible current intensity?

We must, in this case, have regard to the fact that the electromotive force depends only on the number of cells arranged in series or groups of cells in

parallel, but that the internal resistance *increases* according to the number of groups arranged in series, and *decreases* in accordance with the number

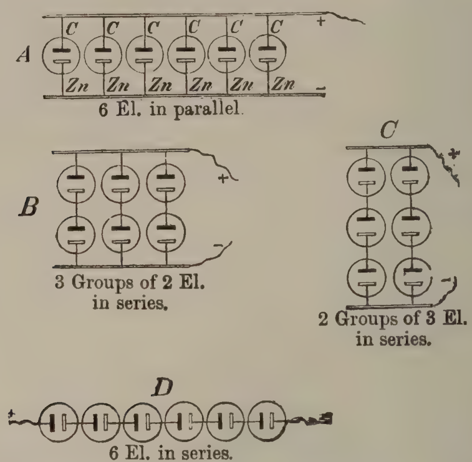


FIG. 123.—Different combinations of six galvanic cells. A, six cells in parallel ; B, three groups of two cells each—in series ; C, two groups of three cells each—in series ; D, six cells—in series.

of elements of each group in parallel ; therefore the current intensity in every combination may differ.

Hence (see fig. 123) we have for six cells the following combinations :—

	In Series.	Parallel.	Electro-motive Force.	Internal Resistance.
A	1	6	E	$\frac{1}{6}w_1$
B	2	3	2E	$\frac{2}{3}w_1$
C	3	2	3E	$\frac{3}{2}w_1$
D	6	1	6E	$6w_1$

According as, in the given case, the external conductor offers a greater or less resistance (w_a), so

will the intensity of current of the battery vary. It would be desirable, of course, to choose in every case the most favourable combination; that is, the one in which the current intensity attains its maximum. Theoretical results by Ohm's law and practical experiments confirm the following rule:—

For a given resistance in the conductor (w_a), *the most advantageous combination of galvanic cells is that in which the total internal resistance of the battery will as nearly as possible equal the entire external resistance.*

Best combination of the cells of a battery.

Let us arrange a certain number p of cells in *parallel*, and h of such groups in series; then the intensity of current is—

$$\overset{h}{\underset{p}{J}} = \frac{h \times E}{\frac{h}{p} \times w_i + w_a},$$

and we get as the most favourable arrangement when the number of similar cells $n = h \times p$—

$$\frac{h}{p} w_i = w_a\,; \text{ or } \frac{h}{p} = \frac{w_a}{w_i},$$

i.e. the cells of the battery at our disposal must be so combined, that the number of groups in series bears the same proportion to the cells in parallel in each of the groups that the external resistance does to the internal resistance of any one cell.

Practical rule for the best combination of cells.

Another example may make this more clear. We have at our disposal a battery of fifty Leclanché's cells, the electromotive force (E) of which = 1·3 volt and the internal resistance w_i or 5 ohms. Suppose the external resistance to be w_a or 15 ohms, what is the most favourable combination?

According to the above formula—

$$\frac{h}{p}=\frac{w_a}{w_i}=\frac{15}{5}=\frac{3}{1},$$

then

Number of cells in series $=h=$	3	6	9	12	15
" " parallel $=p=$	1	2	3	4	5
Number for fifty cells $n=h\times p=$	3	12	27	48	75

That is to say, the best combination is that consisting of 12 cells each in series, and of 4 each in parallel. Hence we can use 48 cells. The greatest current intensity obtainable in this case would be $\frac{y^h}{n}=\frac{h\times \text{E}}{\frac{h}{p}\times w_i + w_a}=$ $\frac{12\times 1{\cdot}3}{\frac{12}{4}\times 5+15}=\frac{12\times 1{\cdot}3}{30}=0{\cdot}52$ current units. As to the units of current intensity, *cf.* p. 266.

We see from this how important it is to be able to *measure* the resistance. But upon what does the resistance of a conductor depend? We have already learnt that the resistance in columns of liquids or in wires increases in proportion to their length, and to enlighten you at once you must know that for uniform conductors the resistance must be proportional to the length of the conductor. Now we have only to examine what influence the *thickness* or the *area* of the section and the nature (*i.e.* the material) of the conductors has.

Let us begin with the more convenient column of liquid. We can make use of the glass trough already employed (fig. 118, p. 255). Examine it carefully. You remark that the surfaces of both zinc plates are varnished and marked in four equal divisions, 1, 2, 3, 4, to serve as guides when the plates are immersed.

I pour into the trough a solution of sulphate of zinc ($ZnSo_4$) up to the first line (A, fig. 124). Now I connect one pole of an immersion cell—that is, the one fitted with a rubber bellows, used for blowing in air to keep the current constant—by a short, thick wire to the galvanometer, and the other pole with the binding screw of one of the zinc plates, and the second plate also with the galvanometer. I arrange for the distance between both plates, which I can read off by the paper scale, to be 2 cm. I mark the deflection on the galvanometer by means of a pointed triangular piece of paper, gummed in such a manner on the glass case of the compass (*cf.* fig. 112, p. 245) that it is exactly in front of the point of the aluminium indicator of the deflected magnetic needle. Now let us double the amount of fluid in the trough, and ask how long the column of liquid must be to offer the same resistance. This we shall find out when the galvanometer shows the same deflection as before. Now we get the *same resistance* in the column of liquid

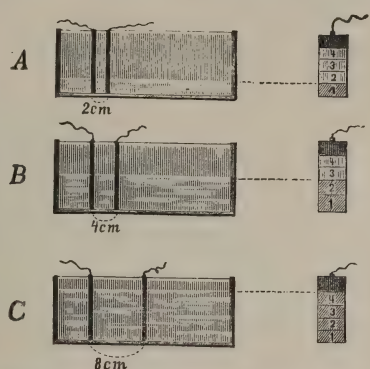


FIG. 124.—Dependence of the resistance upon the area of section of the conductor.

when the area of section $q_1 = 1$ and the length $l_1 = 2$ cm. (A, fig. 124),
" " " $q_2 = 2$ " " $l_2 = 4$ cm. $= 2 \times l_1$ (B, "),
" " " $q_3 = 4$ " " $l_3 = 8$ cm. $= 4 \times l_1$ (C, "),

that is to say, when the resistances are the same the lengths of the conductors are proportional to the section (*i.e.* the area of the section). But if we take

liquid conductors of equal length, then the resistance, when the section is twice as great, will only be half, and when the section is four times the size, only a fourth of the conductor of section $=1$, or, in other words, when the length of the conductors is the same, the resistance is in inverse ratio to the area of the section. We therefore (for the present for liquids only) give the following rule:—

The resistance of a conductor is directly proportional to the length and inversely proportional to the section of the conductor.

$$w = \frac{l}{q} \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

All that remains is to convince ourselves that this is also the case in metallic conductors such as wires. As the resistances in these (as you know already) are much smaller, then, if we do not use very long ones, the inserted wires will only form a small part of the total conductor, and hence will only cause a proportionately small difference of deflection. We must therefore put the deflected needle in that position in which the sensitiveness of the galvanometer is greatest—that is, at an angle of 45° (Appendix, 31, p. 402).

To produce this angle, we must be able to regulate the current; therefore I leave the liquid resistance as current damper in the outer circuit, and lead the wires (as in fig. 125) to the mercury cups sunk in a wooden block B. The circuit will then be closed by the wire *m*, which is to be examined. The two ends of the wires dipping into the cups may be held in their places by springs (*ff*).

As test wire I take a manganin wire of 102 cm.

long, and at about 1 cm. from each end I bend it at right angles, so that the distance between the two bends is exactly 1 m. I now dip the bent ends into the mercury cups (fig. 125) and regulate the distance (D) of the plates until the deflection is exactly 45°.[1]

As in the present case we do not measure the angle of deflection, but only desire to get the same deflection, the commutator is not necessary; we could, also, use any ungraduated galvanoscope we please.

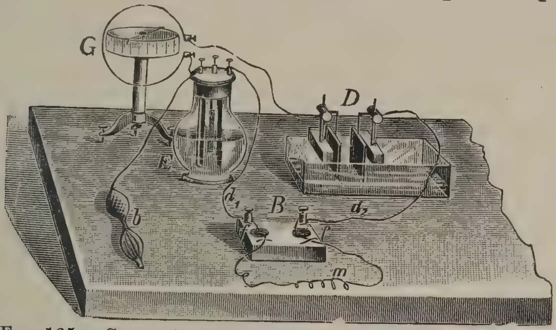


FIG. 125.—Comparison of resistances of wires, $\frac{1}{10}$ natural size (*cf.* note 1). I, substitution method.

Now I take a double wire of the same kind, but twice the length—the deflection being again 45°—and also a fourfold wire, four times as long. I might just as well have taken a single wire of double the thickness, or, instead of the four separate wires, one of a diameter four times as great.[2]

[1] The liquid resistance (fig. 125, D) may be omitted, as by varying the depth of immersion of the plates the intensity of the current may be sufficiently regulated.

[2] If the diameter (the thickness) of a wire $=d$, its radius $r=\frac{d}{2}$, and the area of the section $Q=\pi r^2=\frac{\pi d^2}{4}$. If, for example, the thickness of the wire, $d=1$ mm., then its section $Q=\frac{\pi}{4}$ sq. mm.; but

These wire measurements agree therefore entirely with those of liquids; *i.e. in all uniform conductors the resistance is in direct ratio to the length and in inverse ratio to the area of the section.*

This result is striking in so far that here the galvanic current, speaking figuratively, seems to fill the section of the conductor, *i.e.* flows through the section of a wire, but does not move along its outer surface; whereas we were able to conclude from our observations in static electricity, that the seat of the electricity is there the outer surface of an insulated conductor.

We will now compare wires of different metals with one another. Through the same opening of a draw-plate (a steel plate with holes, with sharp edges of suitable diameter), I have drawn a few wires of copper, silver, German silver, platinum, manganin and iron; they, therefore, have the same diameter, *i.e.* the same section. I take wires of equal length (1 m.) and use them as measures (in fig. 125), and for the silver one I put in the deflection = 45°. If I replace the silver wire by the copper one, the divergence is a little less; still more so with an iron one, and least with the manganin wire; that is to say, the resistance offered by these wires, when their length and thickness are equal, is very varied. To get the same resistance as in 100 cm. of silver wire, we should require 93·4 cm. of copper, 15·2 cm. of iron, 7·0 cm. of platinum, and only 4·2 cm. of manganin wire. In these numbers is reflected also the specific conductive power of these metals, which is inversely proportional

if $d^1 = 2$ mm., then $Q^1 = \frac{2^2\pi}{4} = \frac{4\pi}{4} = \pi$ sq. mm.; therefore the section of a wire of double the thickness is four times as great.

to the specific resistance (*cf.* fig. 127, p. 283). If we denote this specific resistance of a wire by s, the length by l, and the section by q, then the mathematical expression for the resistance of a wire is Specific resistance.

$$W = s \times \frac{l}{q}.$$

As practical *unit of resistance* we take that of a column of mercury 1 sq. mm. in section and 106·3 in length at 0° C., called, in honour of the German scholar Ohm, 1 ohm (usually denoted by Ω).

Resistances are embodied in accurately proportioned wires which correspond to 1, 2, 3, . . . 10, 20, 30, 40, etc., ohms, and are joined together in a case, resistance box or rheostat, so that, by addition, any particular resistance may be interpolated in the circuit. An instrument such as this may be used in connection with the galvanometer, as a make weight is in a scale.

A very useful form of this instrument for school purposes is the adjustable rheostat. An illustration of this as seen from the back is given in fig. 126. Three groups, each containing 10 exactly uniform manganin wires, are arranged so that by moving the three handles (on the front side) we can interpolate resistances of from 0 to 1000 ohms. In a box at the top of the board is an extra ohm fitted on, divided into hundredths with a sliding contact. In this way we can put in successive resistances of from 0·05 to 1111 ohms, and read off fractions of the ohm. We shall soon make use of this apparatus.

The table on p. 279 gives us the power of calculating approximately the length of an ohm in a wire of any size in any of the above metals when its thickness is known.

For instance, we have manganin wire of 0·6 mm. diameter (therefore 0·3 mm. rad.). That gives a section of $0·3 \times 0·3 \times \pi = 0·09 \times 3·14 = 0·2826$ sq. mm. (or, shortly, 0·28 sq. mm.).

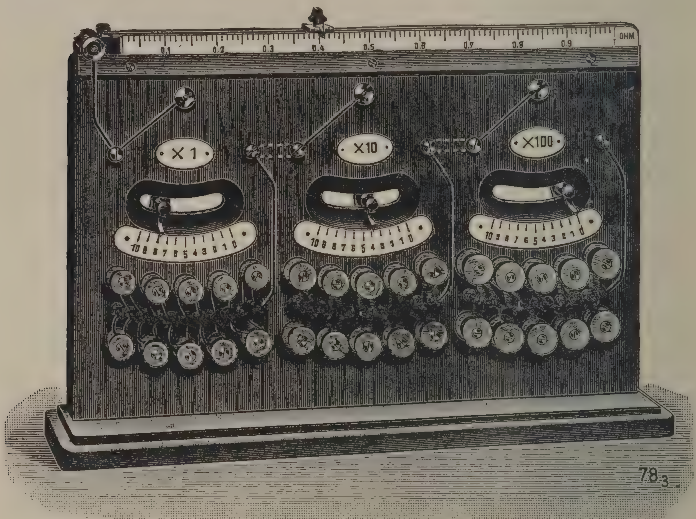


FIG. 126.—Adjustable resistance box or rheostat, back view (complete with scale and connecting wires), $\frac{1}{10}$ natural size.

If the wire (instead of 1 sq. mm.) were exactly $\frac{1}{100}$ sq. mm. in section, then the length required for one ohm would be $\frac{1}{100}$ of 2·34 m. (see Col. II.).

Instead of $0·28 = \frac{28}{100}$ sq. mm. section, we have therefore $x = 2·34 \times \frac{28}{100} = 0·6552$ m., or, in round numbers, 65·5 cm.

The *resistance of a metre* of this wire would, on the other hand, be $\frac{28}{100}$ times smaller than the value (0·427) given in Col. III.

$$\text{Therefore } x = 0·427 \div \frac{28}{100} = 0·427 \times \frac{100}{28} = \frac{42·7}{28} = 1·53 \text{ ohm.}$$

TABLE OF RESISTANCES

ELECTRIC CONDUCTIVITY AND ELECTRIC RESISTANCE.

Material.	Conductivity. In Reference to Mercury as Standard at 0° C.	Conductivity. Length of 1 ohm 1 sq. mm. Section.	Resistance. 1 m. Length 1 sq. mm. Section.	Resistance. In Reference to Copper as Standard.
	I. Hg=1.	II. Metres.	III. Ohm.	IV. Cu=1.
Aluminium . .	30·88	38·82	0·030	1·80
Antimony. . .	2·33	2·48	0·406	23·97
Lead (at 15° C.) .	4·57	4·85	0·206	11·06
Iron (wrought) . .	7·60	8·03	0·125	7·35
Gold. . . .	44·62	47·45	0·021	1·18
Constantan . .	(1·34)	(2·06)	(0·485)	28·30
Copper (soft) . .	55·86	59·38	0·017	1·
Manganin . .	2·20	2·34	0·427	25·38
Manganese steel .	1·39	1·47	0·680	38·00
Brass (wire) . .	12·49	13·28	0·075	4·21
German silver . .	2·44 – 4·18	2·59 – 4·44	0·327 – 0·224	22·5 – 12·7
Nickel (ord. temp.) .	8·62	9·16	0·109	6·48
Nickeline . . .	(2·2 – 1·8)	(2·34 – 1·91)	(0·454 – 0·556)	(25·38 – 31·03)
Platinum (ord. temp.)	6·29	6·69	0·150	8·87
Mercury . . .	1·0	1·063	0·941	55·86
Silver (hard) . .	57·23	60·84	0·016	0·99
,, (soft) . .	63·84	67·87	0·015	0·87
Steel (wire) . .	4·84	5·15	0·194	11·54
Rose's Alloy . .	1·41	1·50	0·667	39·62
Bismuth (wire) . .	0·82	0·87	1·149	67·87
,, (pure) . .	0·43	0·46	2·174	129·90
Wood's Alloy (0° C.)	1·82	1·93	0·518	30·69
Zinc (hammered) . .	16·10	17·11	0·058	3·47
Coke (gas) . . .	...	0·025 – 0·008	38 – 113	...
Sulphuric acid . .	...	0·0000691	14653	...
Zinc sulphate . .	..	0·0000045	208850	...

$$\text{Col. II} = 1{\cdot}063 \times \text{I}\,;\ \text{III} = \frac{\text{I}}{\text{II}}\,;\ \text{IV} = \frac{55{\cdot}86}{\text{I}}.$$

The most important metals for our purposes are printed in thick type.

In the above table the numbers in Col. I. are taken from Landolt and Börnstein (*Phys. Chem. Tab.*), and the other columns calculated to agree.

How the resistance of an iron wire changes when heated, we can easily observe. I put into the

circuit of a cell the galvanometer and a thin iron wire. As soon as the galvanometer has gained a fixed position, I heat the wire with the flame of a spirit-lamp; the stronger the heat of the wire, the less becomes the deflection of the galvanometer. The resistance to conductivity of iron grows with the temperature of the wire, or its conductivity decreases.

According to measurements made by Kohlrausch, the conductivity of iron and platinum is as follows:—

	Platinum.	Iron.
Temperature of a room	6·29	8·80
Red heat	...	0·881
Yellow red heat	2·50	0·820
Beginning of white heat	2·33	0·791

The contrary is the case with many non-metals. Kaolin (china-clay), for example, only conducts at white heat. The carbon filament of those electric incandescent lamps (25 candle power) which have a resistance of 60 ohms at white heat, at ordinary temperature, with weak electric currents, show a resistance of over 300 ohms.

Alloys and their action.

It is interesting that only a few metals (lead, tin, zinc, cadmium) exhibit in their alloys a conductivity which in any way corresponds to the conductivity calculated on the percentage composition of the alloy. All other metals, when alloyed with each other or with those last named, show a much lower conductive power. For example:—

	Power of Conductivity.	
	Observed.	Calculated.
100 parts silver alloyed with 0 vol. per cent. tin	100	100
98 ,, ,, 2 ,, ,,	23·0	98·2
10 ,, ,, 90 ,, ,,	11·5	20 1
0 ,, ,, 100 ,, ,,	11·4	11·4

In the case of certain alloys, as, for example, those of gold with silver, and copper with nickel and manganese, the conductivity of the alloy may be much smaller than that of the component metals. In practice this is important, as from such alloys as nickeline or constantan or manganin normal resistances to be used for measuring can be formed by taking comparatively short wires. Especially valuable for this is manganin (Cu, Ni, Mn), as its resistance alters little between 0° and 45° C.; while the pure metals, as we saw in p. 280, exhibit the very strong influence of temperature upon conductivity.

An alloy of 36 per cent. nickel and 64 steel, called "invar" from its invariability, exhibits an extraordinarily small coefficient of expansion ($\frac{1}{1,000,000}$), for which reason it is very suitable for standard measures, and for the manufacture of pendulums, balances for watches, etc.

We will now examine the relation between the resistance of a wire and the heating occasioned by the electric current.

Heating of conducting wires.

A few conical holes are bored near the edges of this experiment table. In two of them I put turned wooden rods. Between these I stretch a copper wire, about 0·3 m. thick and 1 m. long, and about 15 cm. distance from each an iron wire of the same thickness. On the wires are fastened balls of wax. I now lead the current of a galvanic battery, or, with proper precautions,[1] the electric light current, through the two wires arranged one behind the other in series.

[1] The current may be regulated by putting in 1–10 incandescent lamps arranged in parallel. For safety a short leaden wire should be inserted in the circuit, which will fuse if the heat is too great.

The copper wire slightly bends, and the wax balls gradually melt, while the iron wire sinks down quickly and the wax balls fall away.

Now I darken the room and gradually strengthen the current — the iron wire glows brighter and brighter, at the same time sinking deeper, whilst the copper wire just shows dark red. I decrease again the resistance—the iron wire has entirely fused, at the same time shooting out little bright balls.

We learn from this, that *the greater is the resistance of a wire, the more heat will it exhibit as the electric current passes through it.*

This enables me to put before you at one and the same time the relative resistances of six different metals.

Comparison of resistance. I. Method of momentary observation.

Here you see (fig. 127) a sixfold manometer, the tubes of which are connected by rubber tubing with the tube receivers $R_1 - R_6$ (B, fig. 127). In these receivers are sealed thick, tinned copper wires, connected with corresponding fine wires of copper, brass, iron, platinum, German silver, and manganin respectively. All these wires are of the same length, and, having been drawn through the same draw-plate, are of the same thickness. They are arranged one after the other in series, and hence the same current must flow through all, and they must have the same *current intensity.*

A fall trough or inclined plane is arranged to close the circuit. Along both its sides are strips of nickelled copper (C, fig. 127), and at the upper end, held into its place by a spring (f) between two strips of ebonite, is a nickel-plated brass ball (kg). The free ends of the conducting wires I connect with the

lighting main, or other source of current. A light

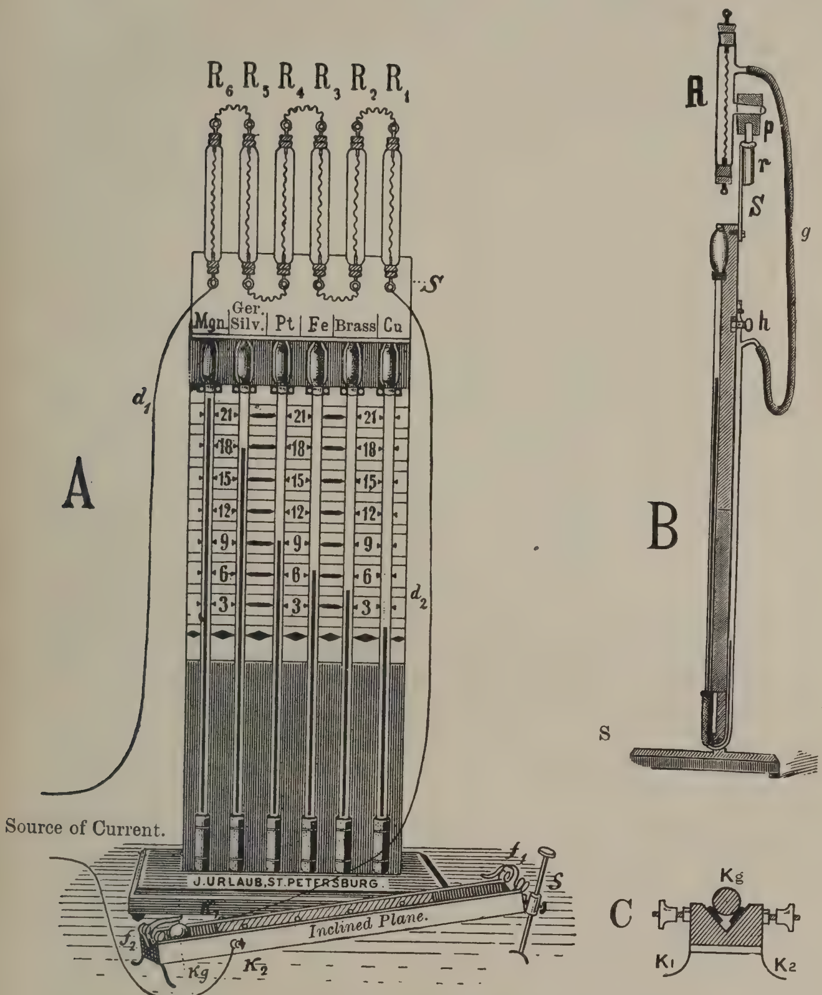


FIG. 127.—Demonstration of the relative resistances of different wires, by means of the sixfold manometer. First method—Momentary observation, $\frac{1}{7}$ natural size.

pressure upon the spring (f_1) sets free the ball, whereupon the circuit is closed for a very short time, while

the ball touches both the copper strips. The duration of contact may be regulated by lowering or raising the upper or right end of the inclined plane.

Now observe the manometer. I let the ball roll—immediately the manometer exhibits, by a variety of risings in the columns of liquid in the tubes, the different degrees of heat, and hence a difference of resistance in the wires.

I had already so regulated the intensity of current and the slope of the inclined plane, that the rise of the column of liquid in the copper-wire manometer was exactly one division of scale. Since the capacity for heat of thin wires and of the enclosed column of air is small, the fluids sink immediately, and after the lapse of $\frac{1}{2}$–1 minute again attain the position of rest.

Now I repeat the experiment, but beg you to fix your eyes on the tubes of the manometer (fig. 127, A). The heights, you observe, are proportional to the heating of the air by the wires, and therefore directly proportional to the resistance of the wires, and in a measure correspond to the fourth column of our table (p. 279).

II. Method according to Lenz and Looser.

Although this experiment is very intelligible and easy to perform, it has this drawback, namely, that it is difficult to keep one's eye on several tubes at the same time. We must, after the receivers are sufficiently cooled, repeat the experiment for each tube of the manometer in turn and note the result.

If the current is weak (1 large immersion cell or 1 small accumulator will suffice), we might also close the circuit for a longer period; still, the unequal cooling of the tubes, as a source of error, during the experi-

ment must be taken into calculation. Also the fine wires may easily melt, or change their resistance.

I will, therefore, modify the experiment.

I remove these receivers and put on a wooden block (fig. 128) with pegs (Z_1 Z_2), below which fit on the two outer tubes (r, fig. 127, B). On the top six brass tubes are sunk in the wood, in which glass receivers stand, which are connected with the rubber tubes of the manometer.

These receivers, first employed by Professor Looser, are double-walled glass vessels of equal height, graduated in c.cm. Into each receiver I pour 30 c.cm. of alcohol, and put in the wires arranged in series through corks. If I connect the current, there appears, in 3–10 minutes, according to the current intensity, the action we observed before, which you can now easily follow.

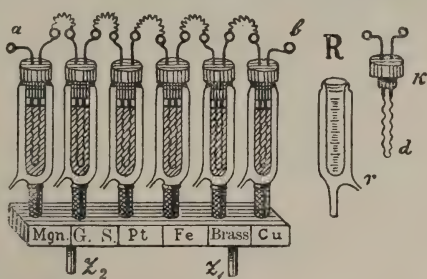


Fig. 128.—Comparison of electric resistances by Lenz and Looser's apparatus. Second method of continuous closure of circuit, ¼ natural size. (The pegs, Z_1 Z_2, are inserted in the upper tubes r, see B, fig. 127).

Now we are in a position to define the *ampère*, which is the practical unit of current intensity.

The practical unit of current intensity, *the ampère, is that current intensity which an electromotive force of* 1 *volt can maintain, when the total resistance is* 1 *ohm.* The ampère as unit of current intensity.

With this definition of current intensity we have for the present only arrived at a theoretical conclusion, for our galvanometer graduation scale, which

we have still to determine, rests upon an *arbitrary* unit.

Measurement of the internal resistance.

To conclude our study of the galvanic cell, we must still settle the question: *How is the internal resistance of a cell or a battery to be calculated?*

According to Ohm's law the current intensity is

$$J = \frac{E}{(w_i + w_a)} \quad . \quad . \quad . \quad . \quad (1)$$

and indeed the best combination of the cells of a battery is that in which $w_i = w_a$; therefore, $w_i + w_a = 2w_i$; then we get for a single cell—

$$J' = \frac{E}{2w_i} = \frac{1}{2} \times \frac{E}{w_i} \quad . \quad . \quad . \quad . \quad (2)$$

But (p. 268) $\frac{E}{w_i}$ is the current intensity of a cell, in the case when the internal resistance $= 0$. This is our fingerpost.

First, we measure the deflection of the graduated galvanometer, in the case when the resistance of the conductor is a vanishing one, when short, thick wires connect the cell with the strong copper ring of the galvanometer. Then we put in the circuit of the outer conductor a known resistance until the deflection is half as great (according to the graduation scale). The total resistance is now doubled and, therefore, the required *internal resistance is equal to the resistance which we had to put in circuit in the conductor.*[1] A second method for determining the internal resistance of galvanic cells we shall study later.

[1] If the instrument used is a tangent galvanometer (as in the next chapter), then we can measure the deflection in degrees corresponding to half the current intensity. Thus we can determine the resistance.

There is another question: How will the current intensity be distributed if the conducting wire is split into many parts, which again become united, as in fig. 129?

You remember we established the fact that in a circuit the same amount of electricity must flow through every cross-section of the conductor in the same time.

Let us imagine both branch conductors (L_1 and L_2) as one single conductor, then through the section of both there flows per second the same amount of electricity as through every other section; therefore, the current intensities of the two branch conductors (i_1 and i_2) are together equal to the total current intensity (J), *i.e.* $i_1 + i_2 = J$. Between the points a and b there exists a fixed potential difference ($v_a - v_b$), *i.e. in both branch conductors the electromotive force* (E) *is the same.* According to Ohm's law the current intensity (i) then depends solely on the resistance (w_1 and w_2). Kirchhoff's law.

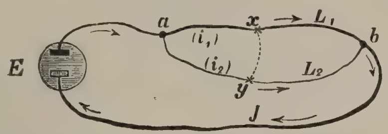


FIG. 129.—Current intensity in branch conductors (L_1 and L_2).

$$i_1 = \frac{(v_a - v_b)}{w_1} = \frac{E}{w_1}$$

$$i_2 = \frac{(v_a - v_b)}{w_2} = \frac{E}{w_2};$$

therefore: $i_1 \div i_2 = \dfrac{1}{w_1} \div \dfrac{1}{w_2}$ (or $i_1 \div i_2 = w_2 \div w_1$).

In the case of *several branch conductors* between two points in the path—

$$i_1 \div i_2 \div i_3 \quad . \quad . \quad . \quad . \quad . \quad = \frac{1}{w_1} \div \frac{1}{w_2} \div \frac{1}{w_3} \quad . \quad . \quad . \quad .$$

This law, discovered by Ohm and put into effect by (and named after) Kirchhoff, gives us a means of measuring with a graduated and very sensitive galvanometer even *very great current intensities.*

If we give to both branch conductors (I, that of the galvanometer, and II, that of the so-called "shunt") resistances which stand in a certain proportion to each other, say $99 \div 1$ (therefore $\mathrm{I} \div \mathrm{II} = 99 \div 1$), then the current distributes itself so that through the conductor with the smaller resistance (the shunt), a current ninety-nine times as great flows as through the other branch (*i.e.* that of the galvanometer). Only one part, namely, $\frac{1}{100}$ of the total intensity $(99 + 1)$ passes through the galvanometer. If we measure the current intensity (i) in the galvanometer, the total intensity $J = 100i$. We shall make immediate use of this convenient method of increasing the extent of the measuring power of a graduated galvanometer (*cf.* figs. 130, 131), but we will first follow the fall of the current in the two branch conductors, L_1 and L_2 (fig. 129, p. 287).

Between the points a and b there exists, as you saw, the same *potential difference.* In the branch L_2 a point (y) of equal potential corresponds to every point of the branch L_1 (*e.g.* x). If these two points (x and y) are connected by a conductor (the "bridge") and a galvanoscope, *then no current will flow through the bridge, i.e.* the indicator of the galvanoscope must remain on the zero point. Then, according to Ohm's law, the ratio of the resistances must be $\frac{ax}{xb} = \frac{ay}{yb}$. This gives us a rule for determining the resistance of a wire (*cf.* also fig. 132).

The action of great resistances upon the current intensity (*cf.* p. 257) and the law of *branch currents* enables us to extend very considerably the range of measurement of a galvanometer.

You see here (fig. 130) a solenoid—or, as it is sometimes called, a moving-coil galvanometer. Instead of a magnetic needle, there is between the poles of a

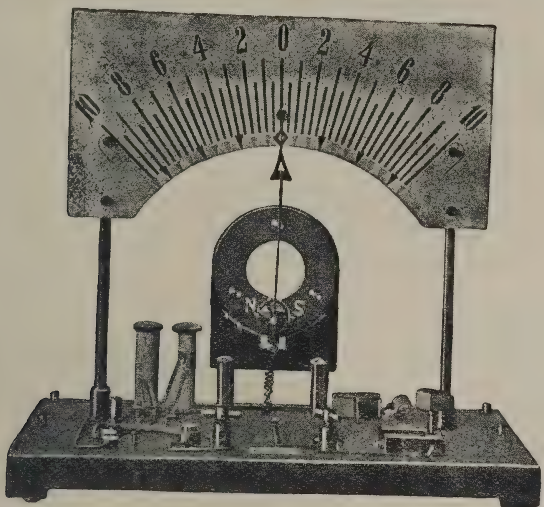


Fig. 130.—Solenoid galvanometer, new form, $\frac{1}{6}$ natural size. Also available as voltmeter and ampèremeter. (The glass cover has been removed.)

strong ring magnet (NS, fig. 131) a solenoid (So), which is made to turn round a horizontal axis by the force of the current (*cf.* fig. 111, C).

The solenoid in this case strives so to place itself *that its current flows in the same direction as the molecular currents of the magnet* (p. 223). To the ends of the axis two fine hair springs (f_1 f_2) are fastened ; they are tightly stretched and coiled in opposite directions. By them the solenoid (zero

position) is kept in position when at rest, *i.e.* when no current traverses it.

The extent of the deflection of the solenoid will depend on the intensity of the current, and one of the springs will be more stretched than the other.

The angles of deflection are directly proportional to the current intensity, as you can gather by looking at the scale, where the distances are the same (fig. 130, p. 289).

The great advantage of this solenoid galvanometer

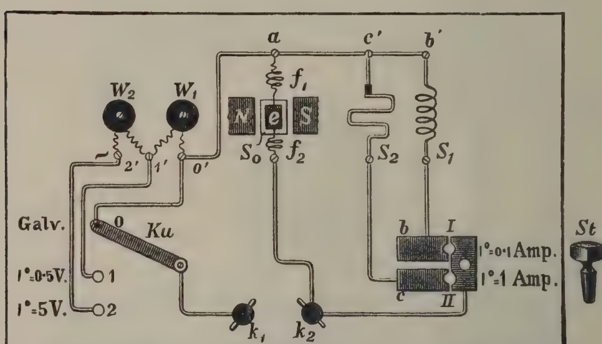


FIG. 131.—Diagram of the switchboard of the solenoid galvanometer, $\frac{1}{6}$ natural size.

over the compass needle is that its oscillations cease much more quickly, and that—on account of the strong directing force of the magnet—*it is not necessary that the apparatus should be placed in the magnetic meridian* (Appendix 33, p. 407).

From the diagram of the galvanometer switch-board given in fig. 131, you perceive that the handle or switch *Ku* may be placed on any of the three metal knobs (0, 1, 2). In the first case (fig. 131), if the electrodes of the cell are connected with the binding screws (k_1 k_2), the current, for example, flows from

k_1, through the switch (by way of 0, 0′, a) and through the solenoid (So) to the binding screw (k_2). In this case the galvanometer only is in the circuit (maximum sensibility).

Resistance previously put in the circuit.

If we place the switch on 1, then the current must flow (over 1′) through the *resistance* W_1 previously put in (in this apparatus 245 ohms), before passing into the solenoid. If the switch is on 2, then both resistances (W_1 and W_2) are put in the circuit (here = 2450 ohms).

Voltameter.

Now we know (p. 257) this: If the external resistance is so great that the internal resistance vanishes, then the current intensity and therefore the deflection of the galvanometer is proportional to the number of cells in series—that is, proportional to the electromotive force. This we measure in *volts*. Now the arranged resistances of this apparatus are so proportioned that (when the switch is on 1) 1 degree of scale corresponds to 0·5 volts; on 2 it corresponds to 5 volts—that is to say, with this galvanometer we can determine *directly* the electromotive force of galvanic cells or batteries, whereby a double range of measurement is at our disposal.

Shunt.

The utility of this apparatus is by no means exhausted by this. You notice on the right of fig. 131 three little metal blocks, quite close to each other, but not touching. I take the plug (St) out of the opening of the right block and place it in the hole I. By so doing an extra conductor is put in circuit from the block b through the spiral wire S_1 (over b' and a), so that a *branch current* is established. The resistance of the thick conducting wires of the switch-board does not come into play. The resistance S_1 in the

Ampère-meter.

shunt (as it is called) is so proportioned (0·18 ohm) that the deviation of the indicator is exactly one degree of scale, if a current of 0·1 ampère flows through the main conductor. If I place the plug in II, in the *shunt* there is a resistance (0·018 ohm) ten times less—therefore 1 division on the scale corresponds to 1 ampère in the main conductor.

The *range of measurement* of the galvanometer accordingly is—

1. As voltmeter . . .	0–5, *i.e.*	0–50 volts.
2. „ ampèremeter . . .	0–1, „	0–10 ampères.
3. „ sensitive galvanometer[1] . .		0–20 milliampères.

In practice the ampèremeter is put in the direct circuit of the effective working conductor, as, on account of the small resistance of its shunt, it has little influence on the current intensity. The voltmeter, on the other hand, is connected by a branch conductor to the poles of the battery (or to the two points whose potential difference is to be determined). On account of the great resistance they put in the circuit, they take from the main conductor a very small portion of its current intensity. The voltmeter when put directly in circuit with the main conductor would indicate correctly the electromotive force only

[1] The resistance of the coil of the solenoid is in this apparatus 9·3 ohms; that of the shunt $S_2 = 0·018$ ohm; consequently the current intensity in the galvanometer branch is only $\frac{0·018}{9·3}$ of the current intensity in shunt S_2, or $\frac{0·018}{(9·3+0·018)} = \frac{0·018}{9·318} = 0·0019$ of the total current intensity. Since (with the shunt S_2) 1 division of scale $= 1$ ampère, then on the *sensitive galvanometer* 1 division of scale $= 0·0019$, or, in round numbers, 2 milliampères. The range of measurement is therefore 0 - 20 milliampères.

for such time as the resistance of the conductor was small in comparison with the resistance offered by the voltmeter. An experiment when the rheostat is put in circuit (fig. 126, p. 278) shows this very plainly.

Determination of the internal resistance, II method.

This volt and ampèremeter puts us also in a position to determine in a very convenient way, *without rheostat,* the internal resistance of galvanic cells. First, we put the switch on 1 (fig. 131), and connect a cell with the apparatus by short, thick conducting wires. We get 4 divisions of scale = 2 volts. We now put the plug (St, fig. 131) in opening II and push the switch on to 0. The apparatus indicates 8 ampères. We have, according to the formula—

$$J = \frac{E}{w_i + w_a} = \frac{E}{w_i}(w_a = 0),$$

in which case w_i, the required magnitude, is

$$8 \text{ ampères} = \frac{2 \text{ volts}}{w_i};$$

therefore

$$w_i = \frac{2}{8} = 0{\cdot}25 \text{ ohms.}$$

This method of determining the inner resistance is subject to limitations, on account of the range of measurement of the ampèremeter. We could not, for example, employ the large immersion cell (p. 262 and footnote), as we can only measure up to 10 ampères.

Although this galvanometer is very convenient, still, I forebore to use it in our early experiments, as its complicated construction would then have been unintelligible to you. Also, on account of the great resistance of the solenoid coil (9·3 ohms), it is not very suitable for proving Ohm's law, in cases where

the external resistance is vanishingly small in comparison with that of the internal. As the interior resistance of an ordinary immersion cell is about 0·4 ohm, the resistance of the solenoid is $\frac{9\cdot3}{0\cdot4} = 23$ times greater.

With the help of this galvanometer arranged as a voltmeter, the experiment on p. 215 (fig. 94) is much simplified.

Wheatstone's bridge.

Kirchhoff's law (p. 287) gives us a means of deter-

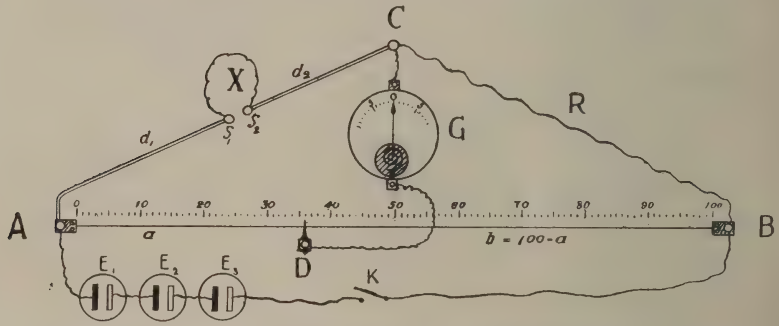


FIG. 132.—Measurement of resistance—II method—by Wheatstone's bridge (zero method). R, rheostat; x, the wire to be tested; G, galvanometer; E_1, E_2, E_3, cells arranged in series ($\frac{1}{8}$ natural size).

mining the resistance in the wires much more accurately than in our experiment on p. 275. The *branch current* used is called, after its discoverer, "*Wheatstone's bridge.*"

Here (fig. 132) you see the diagram of this. Between A and B there are two branch currents, ACB and ADB, in which AD and DB are sections of the same scale stretching from A to B. The wire under examination (X) is connected to the two binding screws s_1 and s_2, and thick copper wires of very slight resistance are joined to A and B re-

spectively. Between C and B a manganin wire (R) of accurately known resistance (*e.g.* 1 ohm) is inserted. To the constant measuring wire AB (which is divided into 100 equal parts) a movable contact (D) is fitted. The galvanometer (g) is connected with the screw C and the movable contact by insulated wires. The three cells (dry or Leclanché's) arranged in series are joined with the binding screws A and B. In the circuit a contact key (K) is arranged.

If we put on the current by pressing down K, the indicator of the galvanometer exhibits a deflection. By pushing along the sliding contact we can render the galvanometer current less (zero method). In this case—

$$\frac{x}{R}=\frac{a}{b},$$

or (since AB is divided into 100 equal parts),

$$\frac{x}{R}=\frac{a}{100-a};$$

therefore

$$x=\frac{R \times a}{100-a}.$$

According to the position of the sliding contact (D) (fig. 132), $a=36$, therefore $100-a=64$, and so we get as resistance of the wire x (under examination), since R $=1$ ohm—

$$x=1 \text{ ohm} \times \frac{36}{64}=0{\cdot}5625 \text{ ohms}.$$

By putting in different resistances for R (*e.g.* 0·1; 1; 10; 100 ohms), the range of measurement of this measuring bridge is much increased. It is only necessary to connect, by means of short, thick wires,

the rheostat (fig. 126) with the screws B and C (when the other wire has been removed).

According to this or a similar method, the resistances given in table (p. 279) were determined.

We have thus finished a long day's journey, and in the next chapter we shall study a new dynamic action of the galvanic current.

CHAPTER V

Heating effect of the galvanic current. Electric incandescent lamps. Electrolysis of water. Detonating gas voltameter and hydrogen voltameter. Electro-chemical equivalents. The volt, the ohm, and the ampère as practical units of electromotive force, of resistance, and of current intensity. Calibration of the electrometer in volts. Comparison of the scale of the tangent galvanometer with the scale of degrees. Tangent galvanometer as measuring apparatus. Reduction factor for the galvanometer. Electro-metallurgy. The electric telegraph (Lesage, Sömmering, Schilling, Gauss and Weber, Steinheil, Wheatstone and Morse). Polarization currents. Secondary cells and accumulators. Thermo-electric currents.

In the last chapter we took as the measure of current intensity, the deflection of the magnetic needle caused by the galvanic current, and after we had transformed our galvanoscope into a galvanometer by graduating it, we discovered—

1. That if a galvanic current flows through a conducting system, other things being equal, the longer the conductor or the smaller its cross-section, the weaker is the effect upon the galvanometer. The cause of this feebleness of current intensity in the conductor we call its *resistance*. In uniform conductors the *resistance is in direct ratio to the length and in inverse ratio to the area of the cross-section.* The resistance (w) and the conductivity (l) of a conductor are in reciprocal proportion to each other ($w = \frac{1}{l}$). Retrospect.

The practical unit of resistance (1 ohm) is a uniform thread of mercury of 1 sq.mm. section and 106·3 cm. in length at 0° C.

2. The *current intensity* (J) is dependent upon the other magnitudes. It is in direct ratio to the electromotive force (E) of the cells and in inverse ratio to the resistance of the whole circuit (W), *i.e.* to the internal resistance (w_i) inside the cells themselves + the external resistance (w_a) in the system of conduction. Therefore the current intensity is

$$J = \frac{E}{W} = \frac{E}{(w_i + w_a)}.$$

It follows from this law of Ohm that the current intensity *will be increased* by the vanishingly small external resistance of cells in parallel, but the opposite when the external resistance is made much greater by their arrangement in series. The grouping of elements in a battery which gives the greatest results is that in which the total internal resistance is equal to the total external resistance of the circuit —that is to say, the number of groups of cells in series must be in the same proportion to the number of cells in every group arranged in parallel, as the external resistance is to the internal resistance of one cell.

3. If the current conductor is "branched" between two points in the path, then the current intensities of the single branches are in inverse ratio to the corresponding resistances of the branches ($i_i \div i_i$ . . . $= \frac{1}{w_i} \div \frac{1}{w_2}$ . . .).

This law of Kirchhoff gives us a means of measuring the strongest currents by so choosing the resistances

of two branch conductors that through the part of the conductor in which we measure the current intensity there flows a well-ascertained fraction of the whole current.

In the last chapter we learned upon what circumstances the current intensity (that is, for the present, only the action on the galvanometer) depends, but our experiments with the galvanometer gave us no foothold on which to base the definition of that current intensity which was to form our *unit*. When graduating the galvanometer we took, arbitrarily, a constant current = 1. The expression *quantity of electricity per second*, which flows through the section of the conductor, is borrowed from its analogy to a stream of water, and hence is only to be considered as a figurative manner of speaking, for we possess no sense-organ capable of perceiving electricity, and therefore cannot measure its quantity directly. It is to be expected that the electric current, which draws the magnetic needle from its position of rest, and lends to iron in its character of electro-magnet such an enormous attractive force, may also produce effects of another kind. Perhaps among these we may discover what we seek; namely, a practical measure for current intensity.

I. Here stand three large Bunsen's cells (*cf.* B, fig. 89, p. 202). I arrange them in series in a battery. To one free pole I fasten a fine metal thread (tinsel, such as is used for Christmas tree decorations). Will one of you kindly screw the other end to the free pole of the third cell? You drop the thread hastily because it has become too hot to hold.

On p. 282 we learned that wires through which a current passes begin to glow, and, if the current is strong enough, to melt. This heating effect of the electric current is taken advantage of in practical matters in the exploding of mines, blasting of rocks, etc.

This is an electric lamp (fig. 133), consisting of a small pear-shaped glass vessel, exhausted of air, in which two platinum wires, connected by a delicate hair-like loop of carbon filament, are fused.

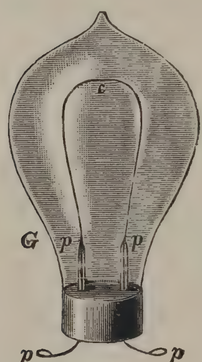


Fig. 133.—Electric incandescent lamp, 2ce natural size (6 volt).

If I turn the current of the three cells into the carbon filament, by connecting the loops of platinum protruding from the glass vessel, it begins to glow with a bright golden light. For household use these lamps, of course, get their power from a different source, which we shall study later on.

The conductor is heated by the electric current, and, indeed, the worse the conductor or the greater its resistance, the greater the heat. You can now guess whither, when we "damped" the current and so put a resistance in the circuit, the apparently lost energy went. *The electric energy*

Joule's law. *was changed into heat.* We might now try to determine the amount of heat generated by a current, but the very laborious and difficult experiments of Lenz and Joule have proved that the amount of heat generated in the current conductor is indeed in direct proportion to the resistance of the conductor, but not to the current intensity itself. It is actually proportional to the *square* of the current intensity;

and accordingly the experiment is not suitable for our present purpose.

II. We will now study a chemical and dynamical

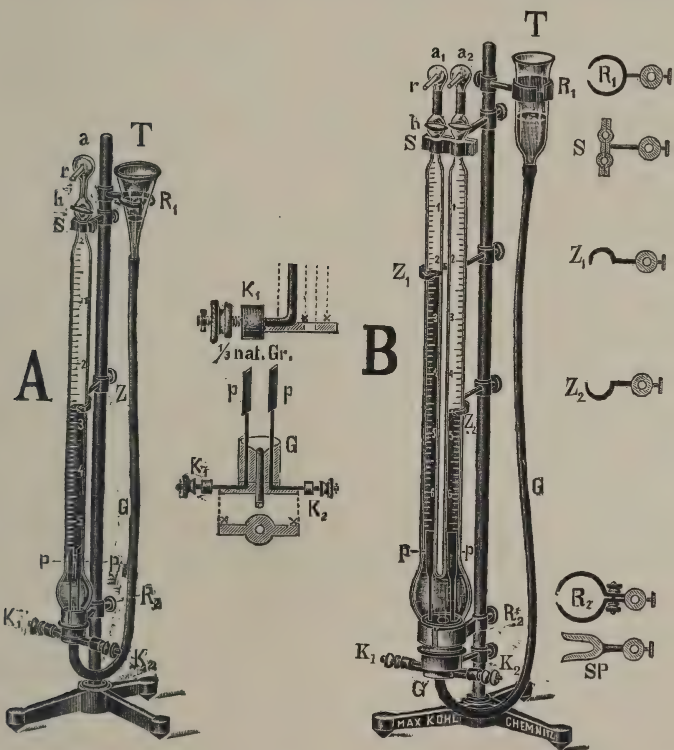


FIG. 134.—Electrolysis of water, $\frac{1}{10}$ natural size. A, detonating gas voltameter, new shape ; B, hydrogen voltameter, new shape.

effect of the galvanic current, or what is called the decomposition or *electrolysis of water.*

You see here (A, fig. 134) a glass tube closed at the upper end by a stop-cock ; while the point into which it is drawn out connects with a hollow glass ball (*a*) by a rubber tube not shown in A. The glass tube Gas voltameter.

is graduated in fifths of a cubic centimetre. The lower end of the tube widens out into a ball-shaped distention, and thence contracts into a neck. A spring clamp (R_2) holds this, whilst beneath the tap at the top a screw clamp (S) binds the tube to the holder. Into the lower orifice a funnel-shaped rubber stopper with holes bored in it (see G, centre figure) is pushed, and through this waterproof stopper are inserted two strong copper wires carefully painted over with amber varnish: these are soldered to the platinum strips or electrodes (*p p*). The outer ends of the copper wires are provided with nickel-plated binding-screw terminals (K_1 K_2). The small glass tube of the rubber stopper is joined by a rubber tube with the funnel T, which, with its connecting ring (R), may be raised or lowered, or taken out of its holder altogether.

I pour distilled water into the funnel and open the stop-cock until the tube is full. I now connect the binding-screws with the electrodes of three Bunsen cells arranged in series (fig. 135, p. 306). You notice no effect, and the galvanometer inserted in the circuit shows no current—that is to say, chemically pure water does not conduct the electric current, and is not decomposed by it. I interrupt the current and take off the funnel while the stop-cock is opened.

After all the water has flowed out, I put the funnel in its place, fill the apparatus with diluted sulphuric acid (strength 10%), and close the stop-cock. Observe the apparatus. If I now close the circuit, we see a turbulent movement in the column of fluid, because from the platinum electrode a brisk flow of gas rises. In a few minutes we obtain nearly 30

c.cm. of gas. This apparatus works very energetically, as the distance between the platinum plates is only 2 mm.; therefore the resistance of the wall of fluid lying between is comparatively very small.

What kind of gas is this? I take a tube of strong glass 180 mm. long, 20 mm. internal diameter, closed at one end, and enclosed in wire netting, which I wrap in a cloth. Upon the little tube (r) of the ball (a) (fig. 134) a piece of rubber tube has been slipped, and this I push into the glass tube. Then I open the cock, and keep it so until all the gas has escaped into this last. I take away the tube and put the flame of a candle to its opening—a loud report follows, like a pistol shot, but on account of the precaution we took, the explosion does no damage. Let us examine the tube. You see it is cracked and small drops of moisture have condensed on the sides of it. We have not, therefore, to deal with a simple gas. The water has been decomposed into its parts, hydrogen and oxygen, which have again united as moisture. The compound of hydrogen and oxygen is called detonating gas. The apparatus used by us is, therefore, called the detonating gas voltameter. Oxyhydrogen gas.

In this case a complicated process has been gone through. The electric current decomposed the sulphuric acid, which chemically decomposed the water in order to regenerate itself. But the final result is as if the sulphuric acid had remained unchanged and only the water had become decomposed; hence the name, decomposition of water.

To keep the two gases separate we make use of another apparatus (B, fig. 134, p. 301). A tall U-shaped glass tube, with both its legs equipped as in Hydrogen voltameter.

the former case, has at its lower end a rubber stopper supported by a strong two-pronged holdfast (SP). The platinum electrodes ($p\,p$) extend up into the legs. The funnel T at the top is larger than the other one, for its capacity must be equal to that of the two legs of the tube.

I fill the funnel with diluted sulphuric acid (10 per cent.) and open both cocks until the legs are filled. As soon as I put the current through, you see a brisk flow of gas ascending in both legs, but from the positive electrode or the anode it is much less than from the negative or kathode.

I raise the funnel until the level of the fluid in it is about 1 cm. higher than the taps (B, fig. 134, p. 301). When about 20 c.cm. of gas have been generated by the kathode, I open both taps carefully and let the gas escape. I repeat this several times, until (in about five minutes) the fluid in both legs is saturated with the gas[1] passing through it.

Now we can proceed with the experiment proper. When the taps are closed, I interrupt the current, until the gas bubbles have collected at the top, then I let the gas escape and close the taps. Now look at the clock.

I turn on the current. In three minutes I stop the

[1] Water absorbs gas, especially oxygen. If we had performed the experiment immediately, the amount of oxygen received would have been *too small.* The fact that oxygen is absorbed much more strongly than nitrogen by water, is of great importance for animals and plants dwelling therein. While atmospheric air contains only 1 part by vol. of oxygen to 4 parts of nitrogen, the air obtained (by means of an air pump) from fresh or sea water contains considerably more oxygen than the atmospheric air (about 33 per cent.).

current and wait until the gas bubbles have risen up. On the kathode there is about 40 c.cm. of gas. Now I lift the funnel out of the ring and hold it near the tube, so that the surfaces are at the same level. At the kathode there are now 42 c.cm. of gas; at the anode 21 c.cm., *i.e.* only half as much. By getting the surfaces of both columns of fluid at the same height, the gases in both legs are measured under the same pressure (1 atmosphere). Upon testing, the larger quantity is found to be hydrogen, the smaller oxygen. Water consists of 2 parts *by volume* of hydrogen to 1 part of oxygen.

The quantity of detonating gas, at the first experiment, or the quantity of oxygen, which is set free in a given time, for example in one minute, may serve as measure of the *current intensity* (Jacobi's current unit yields 1 c.cm. of detonating gas per minute); but this process is less suitable for accurate measurements than that described at length below. To get results capable of being compared, the gases must be quite dry, and measured at a temperature of 0° C. and 760 mm. barometric pressure, or they may be reduced by calculation to this temperature and pressure.

These, as also the following apparatus, ought to be called chemical current-meters. The name "Voltameter" usually given is very unfortunately chosen, as Volta had nothing at all to do with its discovery. It is also liable to be confused with voltmeter, *i.e.* an apparatus for the determination of the electromotive force in volts, such as the solenoid galvanometer, with resistance inserted in circuit.

III. I now replace the electrolysis apparatus by a vessel (A, fig. 135) containing a concentrated solution Copper voltameter.

of sulphate of copper, in which two bright plates of sheet copper are immersed. I put in the circuit also the commutator (C) and the galvanometer (D), as in fig. 135.

This apparatus is called a *copper voltameter.*

We have learned in the preceding experiments how to reverse the current in the galvanometer while its direction remains unchanged in the copper voltameter (A). By moving the copper plates in the voltameter together I can diminish its resistance, and therefore increase the current intensity until the galvanometer

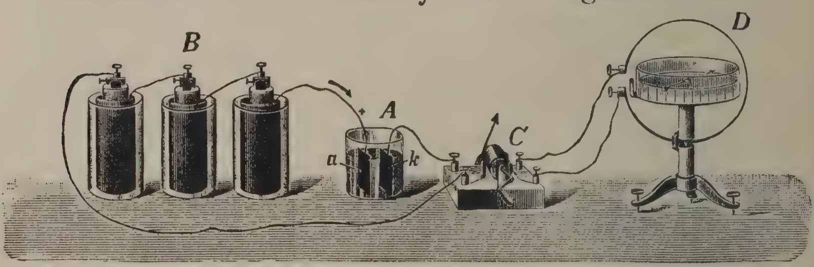


FIG. 135.—Copper voltameter (A). Galvanometer (D) connected with the battery (B) by the commutator (C) in such a way that the current only reverses the direction in the galvanometer. [Distance of copper plate (a k) = 5 mm.]. $\frac{1}{10}$ natural size.

reaches its most sensitive deflection (45°, *i.e.* about 8 units of scale). In a few minutes I take out the plates, clean them, and dry them by wiping them with filter paper and warming them over a spirit-lamp. Now I pass the plates round, but please take hold of them, especially the negative electrode (known by its smooth copper surface), at the place where the conducting wire, covered with sealing wax, is soldered on. You will remark at once that the kathode is covered with a fresh film of copper, while the anode appears as if it had been eaten away by the acid. On the plate on which the (positive) current operated

copper was set free and deposited on the other plate, while apparently the solution of copper has remained unchanged. The metal goes with the current.

We will now determine the additional weight received by the kathode or negative plate. On the side table there is a very sensitive balance. I place the plate upon one of the pans, and upon the other shot or sand, until the two balance each other. Now I place each plate in its place and again regulate their distance, until the deflection on the galvanometer reaches 7·5 divisions (44·6°). After reversing the direction of the current we get 7·6; therefore a mean of 7·55. Now let the current pass through for five minutes, and observe the galvanometer at the end of each minute:—

	I. Current Direction.	II. Current Direction.	Average.
At the beginning . . .	7·5	7·6	7·55
After 1 min. . . .	7·4	7·58	7·49
„ 2 „ . . .	7·45	7·5	7·48
„ 3 „ . . .	7·4	7·5	7·45
„ 4 „ . . .	7·4	7·5	7·45
„ 5 „ . . .	7·35	7·45	7·40
The current is interrupted.			
	Average . . .		7·47

When again wiped and dried in the same way, the kathode plate weighs now about 0·565 gr. or 565 mg. more than before. This amount of copper has been deposited in five minutes, therefore the amount of copper given up in one minute = 0·113 gr. = 113 mg., or $\frac{113}{60}$ = 1·88 mg. per second.

The additional weight of the negative electrode would have been much greater if we had made use of

two silver plates in a diluted solution of nitrate of silver (lunar caustic). For accurate current measurements, therefore, Poggendorf's silver voltameter is employed.

As we recently saw, the current intensity depends on the electromotive force and the resistance of the whole circuit ($J = \frac{E}{W}$). Therefore, for two of these magnitudes we can choose arbitrary units, as the third magnitude is already determined. Let us take, for example, as unit of electromotive force the cell of a Daniell's battery, and as unit of resistance that of a thread of mercury with a cross-section of 1 sq. mm., and a length of 106·3 cm. (1 ohm); then, if the resistance of the whole circuit is known, together with the electromotive force of the battery used as defined by the electrometer, we can calculate (of course in terms of the usual arbitrary unit) the current intensity for every single case. But as resistance measurements are full of detail and require special apparatus, it is often desirable to find a means of measuring the intensity of a battery with the conductor put directly in circuit. The deviation of the magnetic needle of the galvanometer, known as "galvanometric action," would be very convenient, but for the present it gives us only an arbitrary measure, so that the measurements obtained from so many different instruments cannot be compared without further arrangements. We must therefore look about for absolute measures.

We already know that the practical unit of electromotive force, or the potential difference at the free poles of a battery proportional to it, is called the *volt*; still, in static electricity we were totally unable to

meet with a source of electricity, the electric level of which could always be restored. But the constant cells, especially Daniell's, provide us with an excellent source of the kind required. We might simply adopt as practical unit the electromotive force of a Daniell's cell, and reasons of a merely theoretical nature have been the cause of our taking a somewhat smaller electromotive force as more suitable for the practical unit, namely, the *volt*.

The volt as practical unit of electromotive force.

$$1 \text{ volt} = \frac{1}{1{\cdot}07} = 0{\cdot}934 \text{ of a standard Daniell's cell.}$$

Our *aluminium electrometer*, when being graduated with the normal condenser, yielded for 1 Daniell a deflection of $\alpha'_1 = 15°$; from this, the deflection for 1 volt is calculated as $\alpha_1 = \frac{15°}{1{\cdot}07} = 14{\cdot}02°$, or, in round numbers, 14°. This formed the basis of the graduation (p. 77); therefore our projection graduation scale on the electrometer is also a volt scale, *i.e.* when the standard condenser is used (see footnote, p. 77). The divergences on the electrometer observed by us earlier, for various galvanic cells, correspond accordingly to the electromotive force of the cells in volts.

Volt scale of the electrometer.

As *unit of current intensity* we can imagine that current intensity which is produced by a constant cell of the electromotive force = 1 volt, when the whole current resistance = 1 ohm. It is called ampère, after the French physicist Ampère.

Unit of current intensity.

By experiments which I cannot describe to you here, it has been found that a current of this intensity = 1 ampère.

Electro-chemical equivalents.

	Eliminated.		Formed.		Decomposed.
	Silver.	Copper.	Oxyhydrogen Gas.	Hydrogen.	Water.
In 1 min.	67·08 mg.	19·68 mg.	10·44 c.cm.	6·96 c.cm.	5·598 mg.
In 1 sec.	1·118 mg.	0·328 mg.	0·174 c.cm.	0·116 c.cm.	0·0933 mg.

These numbers are called the electrochemical equivalents of silver, copper, and water, and with their help the current intensities of the cells employed can be calculated, as we shall see immediately.

At last, then, we have found for these magnitudes, which are so important for us, the corresponding practical units or measures.

If we designate the *quantity of electricity* per second flowing through the section of the conductor at the rate of one ampère as one coulomb, then the *current intensity = the number of coulombs per second.*

The unit of electromotive force is 1 volt (about 0·9 Daniell).
,, ,, resistance is 1 ohm.
,, ,, intensity of current is 1 ampère.

Now (p. 150) 1 coulomb = 3000 million electrostatic units of quantity of electricity. In order to realise what this immense quantity of electricity means, imagine two coulombs of like electricity at a distance of 1 kilometre. These would exercise upon each other a force of repulsion equal to a force capable of lifting a weight of 900 kilogrammes.

During the last experiment our batteries deposited in five minutes 565 milligrammes of copper, or 113 in one minute. The current intensity, therefore, averaged $\frac{113}{19·68}$ or 5·7 ampères: that is, 5·7 coulombs flowed every second through a section of the conductor.

You now understand what a rich source of electric supply we have in the unpromising-looking galvanic cell, and therefore you will cease to wonder at the wonderful lifting power of electro-magnets.

We might have employed as ampèremeter the solenoid galvanometer (fig. 130, p. 289) instead of the tangent galvanometer, but we should have had to settle the value of our calibration scale, and the fine wire of the solenoid might have been affected by the continuance of the current.

I again remind you of the fact that—even when constant cells are employed—the current intensity has no constant value; nor can it, unlike electromotive force, have any, since *a change of current intensity follows every variation, either in the circuit of the conductor or in its resistance.*

Let us again turn our attention to the galvanometer. While a current of 5·7 ampères flowed through the circuit, our galvanometer averaged (when the ring was in its normal position) 7·47 divisions of the scale; therefore one unit division of scale $= \frac{5{\cdot}7}{7{\cdot}47} = 0{\cdot}763$ ampères. We might employ this number as a *calibration constant* to reduce the readings of the instrument to ampères. Calibration constant.

Our galvanometer is so constructed that both ring and compass can be placed horizontally, so that, with the help of the fixed sight (fig. 112), the angle of deflection can easily be read; also the ring itself can be lowered to decrease the divergences, *without*, at the same time, *altering the resistance in the current.* By this means the graduation is very much facilitated. But as all galvanometers have not this arrangement,

it will certainly interest you to learn what relation the angle of deflection, read off in degrees, bears to the current intensity.

I project (fig. 136) on the blackboard the quadrant of a circle, divided into degrees 0° to 90°, and set off along the circumference the values of the scale found when we were graduating. Then I draw a line AB parallel to the diameter r, passing through the zero point 0, and from the centre M, I draw radii through the scale points to line AB. The

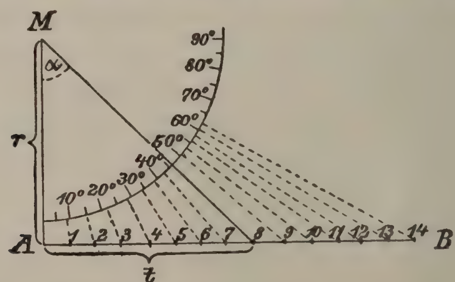


FIG. 136.—Relation between degree scale and calibration scale in the tangent galvanometer.

points at which the radii cut the line, I mark with the corresponding figures 1, 2, 3, etc.

You, of course, understand that from AB almost exactly equal portions are cut, *i.e. the sections of the line* AB (counted from point A) *are proportional to the calibration degrees, and therefore proportional to the current intensity.* A section t of the line AB corresponds to a deflection of the galvanometer, observed in degrees, $=\alpha^0$. Now the value of the fraction $\frac{t}{r}$ is the so-called trigonometrical tangent of the angle α ($\frac{t}{r} = \tan\alpha$).

If now a current of the strength J causes a deflection $=\alpha^0$, then the corresponding distance on

AB $= t$, and is proportional to the current intensity; similarly also the fraction $\frac{t}{r}$ (since the radius r has a constant value). Therefore the trigonometrical tangent of the angle α^0 ($\tan \alpha = \frac{t}{r}$) is a measure of the current intensity.

Current intensity $J = k \times \tan \alpha^0$.

Where k is a constant factor, depending on the dimensions of the apparatus, and called the *reduction factor* of the compass.[1] We can therefore call the compass a tangent compass or tangent galvanometer (Pouillet, 1837).

Reducing factor of the tangent galvanometer.

More accurate measurements prove that for galvanometers of this kind, the (trigonometrical) tangents of the angle of deflection are actually proportional to the corresponding current intensities, but only when the magnetic needle is very small in comparison with the diameter of the conducting ring. And in our apparatus this is the case, because the length of the needle is scarcely a tenth part of the diameter of the ring. Hence the uniformity in the length of the sections of AB (fig. 136, *cf.* Appendix, 36, p. 409).

IV. Our copper plate is still lying on the scale pan. I take it up and bend it about. You hear a crackling, and, look! a delicate copper film comes away—that is, the thin layer of copper just deposited may be pulled off bit by bit, and exhibits with photographic exactness an impression of the coarse copper plate. But what in the plate before were reliefs are now depressions, and what were depressions have become reliefs.

Electro-deposition; electrotypy.

[1] If $\alpha = 45°$, $\tan \alpha = 1$, therefore $J = k$, *i.e.* the value of the factor k indicates the intensity which causes the deflection of 45° in the galvanometer.

This observation, first made by de le Rive (1836), simultaneously gave the idea to Jacobi in Russia and Spencer in England of taking by electrotype metallic impressions of different objects, such as medals, etc., and in this they were successful. Jacobi called this process galvanoplasty (electro-metallurgy), foreseeing that this galvanic picture-making would give rise to a new industry. Look at the figures in this book. They are woodcuts; but not a single one of the boxwood blocks, upon which the drawing has been engraved, is used for printing from, but an impression was first taken from the woodcut, which shows all the reliefs as depressions and *vice versa*, and it is therefore called the *negative*. The wood engraving is well rubbed with oil and then pressed into a plastic hardening mass of heated caoutchouc, plaster, paste, etc., and the negative so obtained made conducting by brushing it over with graphite or bronze powder. Of this is formed by the above means the positive or cliché of copper, or (by a special process) of zinc.

Phototype. Phototyping or autotyping is a particular branch of this art. A photographic negative is first laid upon a film of bichromated gelatine, which is very sensitive to light, and is exposed for some time. It is then placed in water, and the parts not affected by the rays swell up, while the other parts appear as hollows. The same action may be observed when developing a photographic plate while still damp. When the gelatine film has been hardened by dressing it with formaldehyde, an electrotype impression is made from it, which is called the cliché or stereotype plate. As a great many more impressions can be made from a

metal plate than from a wood-block, and from a negative as many positives of equal excellence as are required can be taken at any time, the advantage of this invention will be clear to you.

The copper plates formerly employed in printing geographical maps required much time, were very expensive, and, after all, only yielded a small number of good impressions. Every new plate involved the same expense as the first, and even then an exact reproduction was impossible. Now a single plate, though the initial cost is twice as much and involves twice as much preparation, gives sharply defined and accurate pictures from which a negative may be formed, and from which positives (either clichés or galvanotypes) may be made in any number, all being of equal excellence. Hence we can now get Galvanotype. school atlases of extraordinary excellence at a merely nominal cost. And, to give another example, books, whose contents do not change, as, for example, tables of logarithms, may be revised and corrected as accurately as possible, and then a galvanotype impression made; so that for subsequent editions an entirely faultless copy is assured which is called stereotype, and the dearer movable types may be taken out and used again, whereby much time and expense is spared. It will be known to you that various articles are now silvered or gilded or nickel-plated by this galvanic process, partly to give them a more attractive appearance and partly to preserve them from rust.

V. While on this subject of the technical employment of the electric current, a few words may be said upon one of the most interesting and important

inventions of the nineteenth century, namely, *long distance writing* or the electric telegraph.

The need of some method of transmitting news with the greatest possible swiftness from one place to another led to the construction of the optical telegraph, which remained in use until the year 1837, and is in some cases still employed, as on the battle field or in scientific expeditions. But the time employed in making the signs and the uncertainty of its working properly—for example, during thick fogs—made it desirable to discover some means of applying electricity to telegraphy; and thus, close upon the heels of many other striking discoveries in the domain of electricity, there followed experiments with the above object.

Historical.

Lesage of Genoa (about 1774) constructed the model of a telegraph, consisting of twenty-four wires, connected at their two ends with a letter of the alphabet and an elder-pith pendulum. The wires were connected to the conductors of a frictional electric machine, which caused the pendulums at the ends to diverge. This experiment looks more like an interesting plaything than otherwise, and was of little practical use. No more fortunate were others, who tried to employ the discharging spark of the Leyden jar to give signs. The high potential of this source of electricity requires such an elaborate system of insulation for the wires, that for practical purposes it cannot be obtained, and therefore experiments with static electricity were soon abandoned.

As at first (until 1820) only the chemical action of the galvanic current in the decomposition of water was known, it will not surprise us that the first electric telegraph was founded on this principle. Sömmering

of Munich (1809) constructed the first workable electric telegraph. He connected the two stations by thirty-five conducting wires, the ends terminating in platinum electrodes placed in a glass trough filled with acidulated water. Whenever an electric current was passed through any pair of these electric wires, little bubbles of oxyhydrogen gas arose at the corresponding electrodes, thus making prearranged signs on a finger-board provided with letters and figures. But, as you may suppose, the time taken to manipulate this proved longer than that in the case of the optical telegraph, and in fact the device was never practically employed.

Sömmering's electro-chemical telegraph.

Scarcely had Oersted (1820) made known his discovery of the deviation of the magnetic needle by the electric current, then Ampère proposed to replace the platinum electrodes of Sömmering's apparatus by magnetic needles, though he himself did not perform any practical experiments in the matter. The number of conducting wires would also have increased very considerably the cost of carrying them out.

The first working electro-magnetic telegraph apparatus was constructed by Baron Paul Schilling von Cannstadt in St Petersburg (1832 or 1833), a friend of Sömmering, by whose apparatus his inventive genius had been excited (Appendix, 37, p. 410). Almost simultaneously, and quite independently, Gauss and Weber (1833), established in Göttingen an electro-magnetic telegraph between the Observatory and the Physical Laboratory. This, then, was the first telegraph used for practical purposes. Moreover, they did not use the galvanic current, but the electro-magnetic induction current (see next chapter).

First electro-magnetic needle telegraph.

Fig. 137 gives a general view of Schilling's first telegraph, which is still preserved in the museum of the head telegraph office in St Petersburg. Six magnetic needles hanging by silk threads were fitted with multiplying coils. These, together with a call apparatus (B), were connected by eight wires, one of which was for the return current. A keyboard (C) served to close the circuit. The movement of the

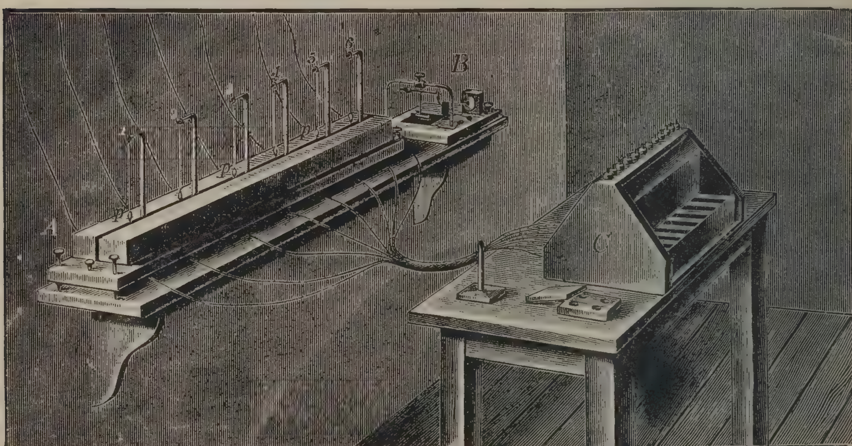


FIG. 137.—First electro-magnetic needle telegraph, constructed by Schilling, 1832–33. B, the call apparatus. From O. Chwolson's *Popul. Vorles, über Elektr.* (Russ.), p. 200.

needles was marked by little cardboard discs (*p*) fastened to the hooks on which the needles hung. When at rest these thin cardboard discs turned their sharp ends to the onlooker, but when deflected their flat sides, of which one was white and the other black. Following this (1835 or 1836) Schilling constructed a telegraph with only one needle. According as it was deflected east or west, signs were arranged corresponding to the letters of the alphabet; but the

inventor was not able to carry this idea to a practical result, as he soon after died (1837).

In 1838, Steinheil of Munich discovered that the second wire of the telegraph circuit could be done away with if the earth was used as return conductor,[1] by soldering strong copper plates to the ends of the wires and sinking them in moist earth or water. This discovery gave great impetus to the development of practical telegraphy.

In 1840, Wheatstone by means of his dial telegraph endeavoured to avoid the inconvenience of specially combined signs. An indicator moved by an electro-magnet marked by its position the figures and letters set round the edge of the dial. This apparatus worked slowly and was untrustworthy

Morse's recording telegraph.

The electro-magnetic telegraphs soon became universal, but in a short time they were replaced, with the exception of the submarine cables, by the recording telegraph, invented (in 1835) by the American Morse, and altered to its present form by Robinson.

We have a model here of Morse's telegraph (fig. 138),

[1] This is not to be understood in the sense that the current really flows from one station to the other, but that the earth acts as a boundless reservoir for the electricity generated by us, whither all surplus electricity flows, or whence every scarcity may be supplied, without any appreciable alteration of its electric potential. To make this clear, imagine a pumping station on the sea-shore, which forces the water into water-pipes, out of which it is again poured into the sea in another place. It is not necessary to believe that the very same particles of water, which flow again into the sea, make their way back to the pumping station and so cause a return current in the sea. This will be clear to you if you imagine the pumping station transferred to the Isthmus of Panama, pumping the water of the ocean into a conduit, through which it is carried into the Gulf of Mexico. Here there can be no question of any return current.

all the subsidiary parts being omitted. If a current is set up in the electro-magnet (M) by pressing the key (S), it attracts the iron armature (a), which is fastened to a lever. In doing this it presses up the little wheel (r) at the other end (till then resting in a suitable colouring matter) against the paper strip (p), which moves, generally by a clockwork arrangement, over the rollers. The distance apart of the rollers (w w) is here made large for greater clearness. If the current is switched on for just a moment the

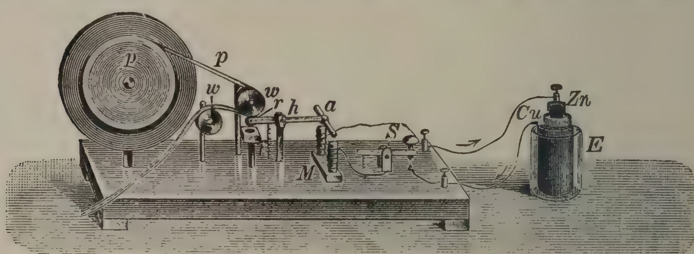


FIG. 138.—Model of Morse's recording telegraph, $\frac{1}{10}$ natural size. M, electro-magnet; L, lever with armature (a) and the small writing cylinder (r), which, when at rest, dips into the ink reservoir; p, roll of paper, from which the strip of paper is carried over the rollers ($w\,w$); S, switch key. (The rollers, $w\,w$, revolve.)

ink-writer makes only a very small point on the paper, while, when the current is closed for a longer period, a *dash* is made. The Morse alphabet consists of "dot" and "dash," as also all signs for figures, punctuation marks, etc. Those letters which occur most frequently are denoted by the shortest strokes, for example, *e* by a dot, *i* by two, *t* by a dash, etc.

In the illustration (fig 139) you have the diagram of a telegraphic system. At A is the transmitting station, whence the message will be telegraphed to B. By pressing down the contact key (S_1), the local battery (B_1) is closed and the current circulates round

the receiving station, whose battery (B_2) is put out of action on account of the position of S_2. The galvanoscopes (G_1 G_2) show the presence of the current.

Although the Morse telegraph surpasses the needle instrument both in quickness and in reliability, yet it did not altogether supersede it, for the force required to put a lever in action is much greater than that required to deflect the magnet needle of

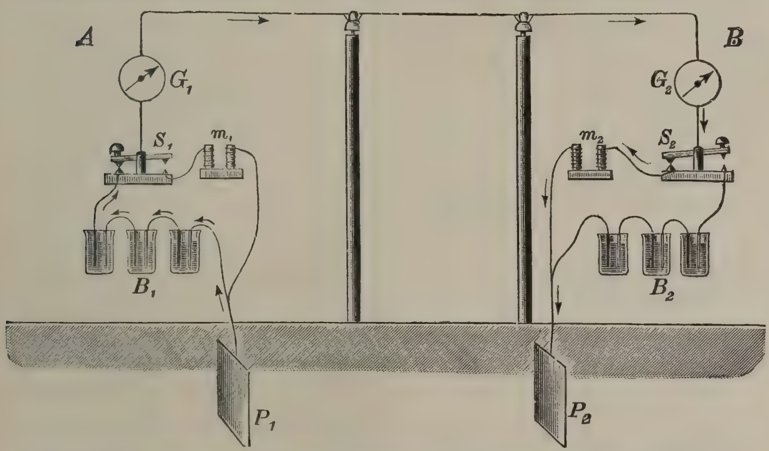


FIG. 139.—Diagram of telegraph system. A, transmitting station; B, receiving station. Switch at A sets current going; at B stops current; B, batteries (in A in; in B, out of circuit); G, galvanometers to show direction of current; P_1 P_2, copper earth plates.

a multiplier. Hence in those cases where only weak currents are available, or where the current may be enfeebled by too great a resistance of the conductor, the needle telegraph is preferable, as, for example, for submarine cables. As both the phenomena and the apparatus employed are in this case very complicated, we cannot go further into the matter without overstepping the limits of this book.

The newest departure in this branch of electricity, wireless or spark telegraphy, will be treated of later.

We will, now that we have gone rather fully into the matter of the employment of the electric current in telegraphy, again turn our attention to the effects of the current, and particularly to those phenomena other than heating the conductor and the so-called decomposition of water, which may make themselves evident.

Generation of the polarization currents.

I connect the positive pole of a large bichromate cell (E, fig. 140) by a wire d_1 with one of the platinum electrodes of the oxyhydrogen voltameter (*cf.* fig. 134), and, at the same time, by a branched wire (d'_1) with the galvanometer. Another wire (d_2) leads from this to the binding screw of the mercury cup. A steel wire is bent into the form of a hook and fastened over the wooden block containing the cup in such a manner that the least pressure will cause it to dip in. The second wire (d_3), coming from the other pole of the cell, is brought up and arranged in the same way, while the connecting wire of the second platinum electrode of the voltameter (d_4) is permanently immersed.

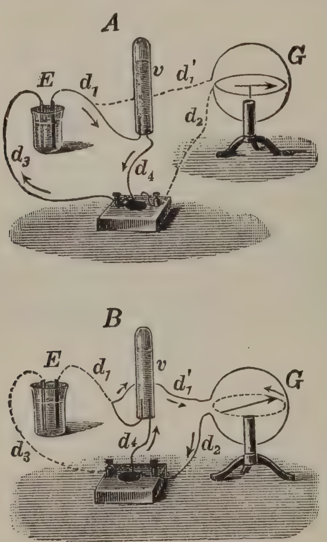


FIG. 140.—Galvanic polarisation, $\frac{1}{15}$ natural size. A, cell (E) and voltameter connected; B, voltameter and galvanometer (G) connected. The open circuits are shown with dotted lines.

I now place my first finger on the hook of the wire d_3 (A, fig. 140), and press it below the surface. Contact is made, and the current flows through d_1, the

voltameter (from R to L), d_4 and d_3, while the galvanometer is out of circuit. The interrupted circuit is shown by dotted lines in fig. 140 (A). If I let the wire hook d_3 spring up, and then immediately press down d_2, then the cell is put out of circuit, and a closed circuit established between the voltameter and the galvanometer (B, fig. 140). Observe:

The galvanometer deflects without being joined to the cell. A glance at the magnetic needle shows you that the north-seeking pole pointed west; therefore the current flows over the needle to the north, and *in the voltameter accordingly from right to left*, i.e. *in the reverse direction to that which it took when connected with the cell.*

We note the same phenomenon if we take a glass vessel, containing a solution of nitric acid, into which the platinum electrodes dip. In this case silver is deposited on one of the plates; therefore in the fluid there are no longer two similar platinum plates, but one clean plate and one silvered. The rise of a current is here intelligible. In the case of the oxy-hydrogen voltameter also, the platinum plates coming into contact with the various gases formed (in one case hydrogen, in the other oxygen) undergo a change of state, although it is not outwardly perceptible, *so that they act, in their electromotive action, like two different metals.* This condition is called *polarization*, and the current appearing when the "polarized electrodes" are joined, is the "polarization current."

As we saw, the *polarization current is opposed to the original current*, and, therefore, it must weaken

it. According to Ohm's law, we obtained for fixed conductors the rule:

$$\text{Current intensity} = \frac{\text{electromotive force of the cell}}{\text{total resistance of circuit}}.$$

But if polarizable conductors are put in circuit in a fluid, then the rule runs:

$$\text{Current intensity} = \frac{\text{E.M.F. of the cell—E.M.F. of polarization}}{\text{Total resistance of circuit}}.$$

By galvanic polarization we must therefore understand such a change of the surface of conductors which dip into a suitable fluid that a current opposite to the original current—the polarization or secondary current—is generated, thus weakening the primary current. As experiment shows, the electromotive force of the polarization current depends on the chemical nature of the immersed plates and the fluid used with them, also in part on the electromotive force of the primary current. When the electromotive force of the primary current gradually increases, that of the polarization current is at first equal to the former, until a certain value is reached, and thenceforward the electromotive force of the polarization current remains constant. For platinum electrodes in distilled water, the maximum is nearly 2·03 Daniells (2·17 volts), but in acidulated water much lower, or about 1·6 Daniell (1·8 volt). If the electromotive force of the primary current is further increased, then visible decomposition of water takes place.[1] Copper plates in a solution

[1] As the electromotive force of a Daniell's cell is about 1·07 volt, by its use we could not attain to the decomposition of water. Neither would the series arrangement in the battery help matters,

of sulphate of copper show only weak polarization, and amalgamated zinc plates in sulphate of zinc solution none at all. Hence we use these as current dampers.

Secondary cells.

The "secondary cells," as the polarization apparatus used for generating the current are called, have, of course, a maximum electromotive force which cannot be overstepped. In recent times they have been put to practical use. Acting on a hint from Sinsteden (1854), Planté (in 1859) constructed secondary batteries of lead plates, which were insulated from each other, and placed in diluted sulphuric acid. If a battery such as this is charged, *i.e.* connected with a source of current, when the positive current enters it, a chemical combination of lead and oxygen (peroxide of lead) will be formed upon the plate, while the other plate is covered with hydrogen bubbles; or if it is oxidized a spongy film of metallic lead is deposited, while the oxide is reduced.

If the primary current is interrupted and a conductive connection made between the lead plates, then there flows through the conductor a current of nearly constant electromotive force (about 2 volts), at the beginning of a higher, although a constantly decreasing current intensity. The direction of the secondary current is naturally the opposite of that of the primary one which charges it, *i.e.* the plate covered with peroxide of lead forms the positive pole.

Accumulators.

Faure, in 1881, improved these secondary cells by

since, by that means, although the current intensity (*i.e.* the quantity of electricity) would be increased, the electromotive force would remain the same.

using, instead of the heavy lead plates, gratings of lead, the surface of which he covered with a film of minium (a combination of lead and oxygen). At the positive pole this is changed directly into peroxide of lead, and at the other pole it is reduced to a very spongy metallic lead, by which the charging is facilitated and quickened. The quantity of peroxide of lead formed is a measure of the electric energy stored up. As this can never be greater than that used for charging, it need not be accentuated. Really a loss of 30 to 40 per cent. of electric energy takes place, which, in the future, will be much diminished, but which is not entirely stopped by better construction of these pieces of apparatus, which are called *accumulators.* One disadvantage of accumulators lies in the fact that, when not in action, a loss of the stored up energy takes place.

If the accumulator current is of shorter duration than the charging current in the galvanic cells used in charging, yet the current intensity, in the beginning at least, is greater. If the accumulators are charged in parallel, then a weaker current of greater electromotive force may be obtained by putting them in series and may be used as desired, as, for instance, for electric lighting purposes. Accumulators, therefore, form a kind of portable magazine of electric energy.

Hitherto we have employed galvanic cells almost exclusively for the generation of the electric current. Now let us look around for other sources for the supply of electricity.

As we saw, the cause of the electric current is the

production of a difference of electric level at any point of a closed conductor or circuit. If this difference of level, as is the case when chemical action takes place in the galvanic cell, is maintained, then the electric current is continuous.

You see here (A, fig. 141) a bow-shaped piece of sheet copper (Cu), soldered strongly to a flat plate of bismuth (Bi), and inside the space enclosed by the metals there is fixed on a steel point a magnetic Thermo-electric current

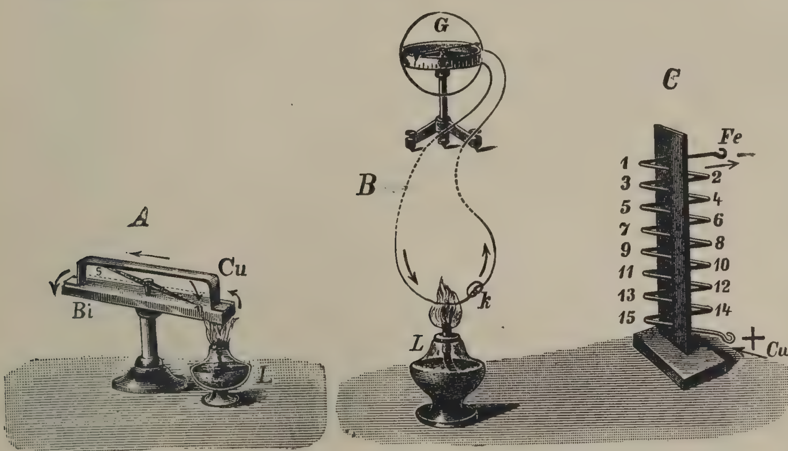


FIG. 141.—A, Seebeck's thermo-electric cell, $\frac{1}{5}$ natural size; B, thermo-electric current in knotted and heated wire, $\frac{1}{10}$ natural size; C, Indrikson's thermopile, 32 (here only 8) pairs of copper and iron wires, $\frac{1}{10}$ natural size.

needle. I place the plate in the magnetic meridian, and heat the northernmost point of junction with the flame of a spirit-lamp. Immediately you see that the north-seeking end of the magnetic needle deflects to the east. Accordingly an electric current has been generated, which flows over the needle to the south, and, therefore, towards the heated junction, or from the bismuth to the copper. The opposite action takes place if I *cool* the point of junction by placing

upon it a piece of ice. These electric currents generated by heat were discovered by Seebeck in 1823, and called thermo-electric currents. The small apparatus (A, fig. 66) is known as the thermo-electric cell, or, shortly, the "thermo-cell."

Experiments performed with the different metals have shown that they can be arranged in such order that when the point of junction is heated, the current always flows from the metal standing lowest in the series to the next above it. By analogy with the electromotive series (p. 16) this succession of metals is called the thermo-electric series.

Thermo-electric Series

$\rightarrow$

(conducting wire)

+ Antimony ← Iron ← Zinc ← Silver ← Gold ← Copper ← Platinum ← Bismuth

Here, too, it may be stated that the further any two members of the series are apart, the greater difference of electric level do they show. Of the above metals a cell of antimony and bismuth gives the greatest effect. The signs + and – denote the kind of electricity at the free poles. In the connecting wire of an antimony and bismuth rod, for example, the current flows from antimony to bismuth, therefore at the point of junction, when heated, from bismuth to antimony.

Thermo-electric currents may also be generated in one metal only, if a piece of wire of the metal is bent or knotted and the bend or knot strongly heated. To show this a very sensitive galvanometer

is required, the winding of which must have a very small resistance. I therefore use our model solenoid galvanoscope (fig. 111, C, p. 239), and replace its solenoid proper by another of only twenty-five windings of strong copper wire (about $\frac{1}{3}$ ohm).

I take another bare copper wire of 0·6 mm. diameter, and about 50 cm. in length (B, fig. 141, p. 327), and make in the middle of it a slip-knot, which I pull quite tight or hammer. I connect the ends of the wire with the terminals of the solenoid galvanoscope (in the figure, for the sake of simplicity, the tangent galvanometer is given). As soon as I apply heat near the knot, the galvanometer shows a sudden deflection.

Much more evident is the effect in the case of a thermo-pile. We have here (C, fig. 141) one I have myself arranged. It consists of thirty-two pairs of copper and iron wires carried through a small board with the ends soldered together. In the figure only eight pairs are arranged and drawn wide apart from each other, so that they may be seen better. The distance apart of the holes arranged in zig-zag in the little boards is 6–8 mm., the length of the wires 50 to 60 mm., and their diameter about 0·6 mm. As all the like points of junction are directed to one side, the approach of the hand at a distance of about 2–1 cm. is sufficient to attain on the galvanoscope a deflection of $\frac{1}{2}$–1 divisions of scale. The approach of the flame of a spirit lamp to the (blackened) junctions causes a deflection of 3–5 divisions of the scale.

With the assistance of a suitable thermo-pile of antimony and bismuth, and a galvanometer adapted to the purpose, very slight differences of temperature

may be shown, so that such an instrument may be used as a highly sensitive differential thermometer. Also stronger, hard-soldered thermo-piles, which can bear a longer heating in a flame, are used to generate constant currents, which can be employed instead of galvanic currents, and are specially suitable for the charging of accumulators. But a more accurate description of these would lead us too far afield.

And so we will conclude for the present. The next chapter will close our course, and in it you will become acquainted with the most powerful of all sources of electrical supply, viz: magneto-electric induction.

CHAPTER VI

Faraday's fundamental experiment. Generation of electro-magnetic induction currents by movement of conductor in magnetic field, by movement of magnet when conductor is at rest, and by change in intensity of magnetism of electro-magnet when both conductor and magnet are at rest. Direction of induction currents (rules of Lenz and Faraday). Inductive action of an oscillating magnet on a copper plate. Self-induction of a coil of wire. Extra current. Induction coil. Action of the alternating current on Geissler's and Puluj's tubes. Röntgen's tubes. Siemens' dynamo-electric principle. Influence of the presence of soft iron in magnetic field on lines of force. Pacinotti's and Gramme's ring. Von Hefner-Alterneck's drum inductor. Different windings of dynamos. Application of the dynamo-electric currents. Electric transformation of energy. The telephone. The microphone. CONCLUSION. Change of hypotheses. Faraday's views as to electric action at a distance. Hertzian waves and wireless telegraphy. Progress in knowledge of the domain of ether waves. Scale of known ether waves.

DURING our later excursions in the region of electricity we have gained a knowledge of the most important phenomena and applications of the galvanic current. A glance backwards will show you that we have often wandered away from the straight path, but do not, on that account, be aggrieved with your guide. If he has led you by by-roads, it was with the intention of giving you new points of view, or because the particular one taken was more passable ; if, again, you have paid a second visit to a point, it was approached from another side, so that you might become perfectly

acquainted with the bearings of the place. On our last journey we learnt that—

Retrospect. (1) The dynamic effects of the galvanic current are manifested in thermal or chemical action. The first kind are seen in the heating and consequent incandescence of a portion of the conductor, when both the resistance and current intensity are sufficiently great. In certain conductors of a liquid nature, the current causes a decomposition of the chemical compounds, and sets free certain elements (electrolysis). By particular processes the metallic parts remaining may be used as a cast (electro-metallurgy), or as a protective covering (galvanoplasty, electro-gilding, plating, etc.).

(2) The quantity of metal, copper or silver, deposited by a galvanic current, or the amount of oxyhydrogen gas given off is proportional to the current intensity. The metal follows the current. Thus, by experiment, a means was found of determining the *electro-chemical* equivalent of the unit of current.

(3) In certain liquid conductors a counter current (polarization or secondary current) was occasioned by the electric current, which continued flowing after the primary current was broken. The strength of the secondary current increases, while that of the primary one is increased until it reaches a constant maximum, which, in the case of lead plates in diluted sulphuric acid or accumulators, corresponds to a difference between the poles of 2 volts. These accumulators may be used as portable stores of current.

(4) The different metals exhibit, when their points of junction are heated, a difference of electric polarity at their free ends, and produce, when conductively connected, an electric current or thermo-current.

With the help of suitable apparatus very small differ ences of temperature, otherwise impossible to detect, may be observed.

Let us now again turn our attention to magnets. We have observed the reciprocal effect of magnets on movable conductors, and have learnt that galvanic currents can call forth from electro-magnets an extra-ordinary portative force. Ought we not also to be able, with the help of magnets, to generate electric currents? This question was often on the tip of my tongue, but first of all I wanted to show you all the qualities of the galvanic current, before entering into this new territory, the peculiar beauty of which might have interfered with your full enjoyment of other electro-dynamic phenomena.

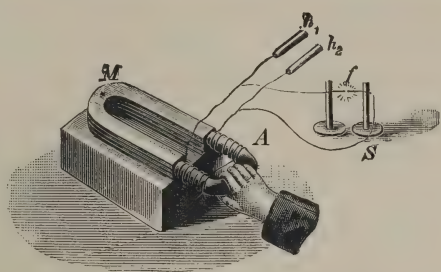


Fig. 142.—Faraday's fundamental experiment in magneto-electric induction, $\frac{1}{10}$ natural size.

Over the entrance gate of this territory there hangs, written in letters of gold, the undying name of the greatest physicist of all times, *Michael Faraday*, the glorious pioneer of electrical knowledge.

We take a horse-shoe steel magnet (M, fig. 142), consisting of several plates fastened together. Its keeper is also horse-shoe-shaped, each leg being wound round with covered wire, in opposite directions, with about fifty windings on each leg.

The wires, ending in brass handles (h_1 h_2), are

soldered to this wire, for use when you wish to act yourself as current-finder.

I grasp the middle of the keeper, and apply it to the poles of the magnet, which I hold fast with the left hand. Take hold of the handles. I tear the keeper suddenly away. You recoil as if struck by an electric shock, and this is really the case. I carry the conducting wires to two glass stands (S), approach their looped ends very near to each other—about $\frac{1}{2}$ mm. Darken the room for a few minutes. As soon as I pull away the keeper again, a spark flashes across—a proof that a current, and, though only momentary, one of considerable electromotive force, has been generated. This is what is called *current at break.* In this fundamental experiment of Faraday in 1831 is contained, as in a seed, the principles of the entire range of modern dynamo-electrical machines.

Our task is now to discover the origin or cause of this magneto-electrical current.

As we already know, electro-magnets are much stronger than steel magnets. I, therefore, wind round an iron rod thirty turns of thick insulated wire (fig. 143), fasten it to a thin stick of fir-wood (S), then run the wire along it, after which I connect it to a large Bunsen's cell. A current-closer, contact key, or switch is put in, so that the circuit may be temporarily closed while our observations are being made. The cell is thus prevented from running down. Let us hold over the electro-magnet a piece of white cardboard, upon which I strew iron filings. I tap it with my finger, and you see that the filings immediately arrange themselves in symmetrical curves, or magnetic lines of force, a

few of which are indicated in fig. 143. If I hold the cardboard still and turn the magnet on its axis, you will see the lines of force rearrange themselves, and, on account of the symmetrical shape of the magnet, in a very similar manner but occupying another plane in regard to position. We learn from this that the *entire space coming under the influence of the electro-magnet is traversed by electric lines of force. This entire sphere of action of a magnet is called the magnetic field.*

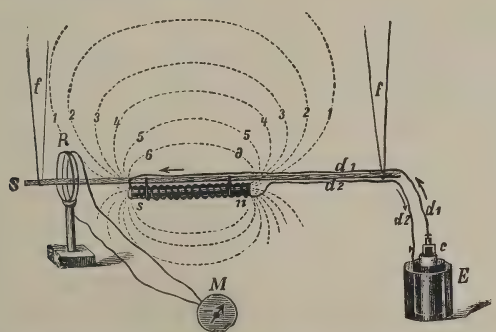


FIG. 143.—Generation of magneto-electric currents by pushing the conductor (R) into the magnetic field, $\frac{1}{20}$ natural size. The wire coil (R) has 100 turns of covered copper wire and an internal diameter of 30 mm.; the electro-magnet has 30 turns.

Now I break the current of the electro-magnet (fig. 143), push the wooden stick through a coil of wire fixed to a stand (R, fig. 143), the internal diameter of which ring is 30 mm., and consists of about 100 turns of insulated copper wire. Then by means of silk threads at either end, I suspend the rod from the ceiling, adjusting it so that it may just come within the centre of the coil. I then connect the latter by long flexible wires with a solenoid galvanometer (M) standing at one side, whereby all resistance is cut out of circuit, and switch on the current (see

fig. 131). We convince ourselves by a compass needle that the pole of the magnet to the right is the north-seeking one, and this I mark by sticking on it a piece of red paper.

Let us now begin our experiments. The coil of wire is just off the end of the south-seeking pole (fig. 143). I put my finger on the wooden stick and push the south pole towards the wire ring. You see the needle deflects immediately, but it comes to rest again if I keep the magnet still. Now I let go the stick—it swings back and the galvanometer needle deflects, but the *opposite* way. While the magnet swings slowly backwards and forwards, during which time the south pole now approaches, now withdraws from the ring, the needle swings in unison, right and left, thus proving that a current at break, the direction of which continually changes, is sent through the galvanometer.

Now I stop the magnet and approach the wire ring and stand to the south pole. A like deflection follows as when the magnet (*i.e.* its south pole) was brought near. If I push it back, a deflection is seen, but in the opposite direction.

If you will observe the direction of the lines of force (fig. 143), numbered successively (1, 2, . . . 6), you will notice that, as the ring approaches the magnet, these lines are cut in the order 1, 2, 3 . . . , but as it is drawn back, it cuts them in the reverse order (6, 5, 4, 3, 2, 1). For the present, then, we may conclude: if the lines of force of a conductor are cut (whether by moving the conductor or the magnet with the lines of force is immaterial), an electric current is generated in the conductor, and

its direction changes as the movement is reversed. This temporary current, generated only by the movement of a conductor in the magnetic field, is called the *magnetic induction current.*

Magnetic induction current.

Now I put a second cell in circuit, in parallel with the first (not shown in A, fig. 143), and leave one wire loose. I push forward the wire ring until it is in the same plane as the pole of the magnet, and let it remain there. Then the needle returns to 0; but if I put in the current of the second cell by inserting the wire in the binding screw, the needle deflects, but flies back at once to zero, only to deflect to the other side if I interrupt the current. What has happened?

In any case the intensity of the magnetic field has been increased by the addition of the second cell. Whence came these lines of force? The soft *un*-magnetic iron exhibits none. They cannot have come from without; hence Faraday concluded that they emerge laterally from the iron rod, when it is magnetized, and are driven back when the magnetism vanishes at the opening of the current. A wire ring surrounding the electro-magnet must therefore be cut *in reverse order* by the lines of force as they emerge and retire; hence the induced currents have opposite directions at the making and breaking of the current surrounding the electro-magnet, and this our experiment shows.

Let us make another experiment to check this. If we place the wire ring, first (R, fig. 143), in the plane of the magnetic pole, and next so that it exactly encircles the electro-magnet, then, in the first case—when the circuit is closed—only a part of the

lines of force meets the wire ring, whereas, in the second case, *all* the lines of force cut it; hence in the latter the induction current must be stronger. Let us test this by using one cell. If the ring is in the plane of the magnetic pole, the deflection is $2\frac{1}{2}$ degrees of scale; but if it is in the middle, $5\frac{1}{2}$ degrees; hence, on our former assumption, much greater.

We can, therefore, repeat our observations in a more comprehensive manner.

While a conductor is cutting through the lines of force, an electromotive force is induced in the conductor, but only during such time as its movement lasts. The direction of the magnetic induction current depends on the order in which the lines of force are cut.

In this we can distinguish three cases:

(1) The magnetic field is moved, while the conductor remains stationary.

(2) The conductor moves in a stationary magnetic field.

(3) The intensity of the magnetic field is changed, while both conductor and magnet are stationary.

All three cases, as we shall see, are employed in the construction of magnetic induction apparatus.

Let us again test the process in our bar electro-magnet, and pay special attention to the direction of the induction current. The south-seeking pole lies to your left. In fig. 144, for the sake of clearness and simplicity, the electro-magnet is shown without its enveloping and conducting wires, and only one turn is shown round the ring.

I push the south pole of the magnet nearer to the

ring (I, fig. 144), or through it (II), then the deflection to the right proves that the current flows from the terminal k_2 (*cf.* fig. 131), into the wire ring, and hence it has the direction shown by the arrow.

While the middle of the magnet is passing through the ring, the needle returns to 0, and when it is pushed

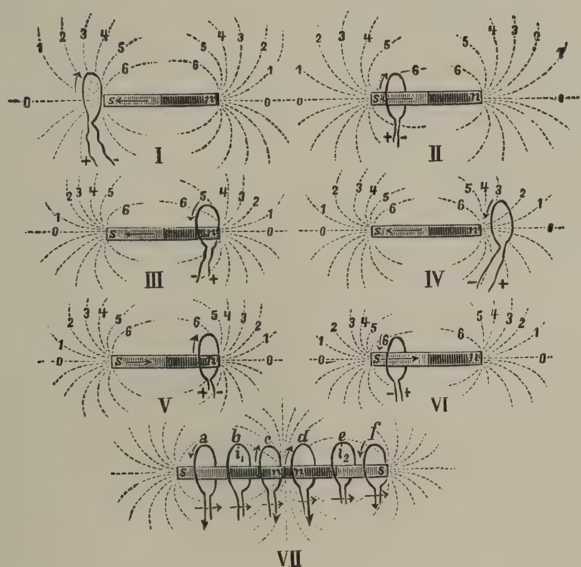


FIG. 144.—Proof of Lenz's law of magnetic induction. In I and IV, the left half, marked by the arrow, is turned to the front.

still further (III and IV) it deflects to the other side, while the ring cuts the lines of force in inverse order.

If I allow the magnet to swing back from left to right (V and VI), the induction current changes its direction.

If you compare (fig. 144, I-VI) the direction of the induction current in the ring marked by a short arrow with that (p. 232) of the hypothetical molecular stream of Weber and Ampère, which in this case is

in alignment with the inducing galvanic current in the enveloping wire, you easily remark :

If the circular conductor approaches a magnetic pole (I), or if the lines of force are successively cut, from outside to inside,[1] by the conductor (I, II, V), then the induction current is opposite to the direction of the magnetic molecular current and to the inducing galvanic current. If, on the other hand, the conductor is withdrawn from the poles, or if it cuts the lines of force from inside to outside, then the induction current is in alignment with the molecular currents and with the inducing galvanic current.

If we use, instead of the electro-magnet, a steel bar magnet, then the effect is much weaker, but the direction of the current the same. If I replace the single magnet by two steel magnets (VII, fig. 144) with their like poles (*e.g.* their north poles) touching, then the neutral points are at i_1 and i_2. If I push the ring along the double magnet, then the induction current $= 0$, and the direction changes when the neutral point is passed.

I put the electro-magnet in again. If I pull the iron rod out of the wire coil and push in a glass tube (in order that the coils may not collapse), we get a solenoid, in which the inducing galvanic current flows as before. The north-seeking pole remains to your left (fig. 143). If I repeat the experiment, the

[1] Here, in a bar magnet (steel or electro), the lines of force curve from one pole to the other, and the magnet is, in a certain measure, wrapped up in them. Let us imagine a section cut through the middle of the magnet (perpendicular to the axis), then those lines furthest from the axis are the *outer ones*. At first glance at the poles they of course look as if they were emerging from the middle.

deflection is much less than with the iron core, and I must connect three Bunsen cells to obtain any appreciable effect; but we see that the direction of the induction current is the same as before. Hence we can formulate what we have gleaned from our observations more concisely, if we remember that currents in the same alignment attract, in the opposite repel.

Lenz's law of induction currents.

At every movement of a current conductor or of a magnet in the neighbourhood of a wire coil (*or* vice versa), *an induction current arises. The direction of the induction current is such that it would give to the inducing current or to the magnet a movement towards the opposite direction* (Lenz). If, for example, a north pole is brought near to the wire ring, then the induction current is opposite to the molecular currents and so tries to repel the magnet. If the north pole is withdrawn, then the induction current is in alignment with the molecular currents and endeavours to attract the magnetic pole. It follows from Lenz's rule, that in the movement of the conductor in the magnetic field resistance must be overcome. The work performed in doing this is the cause of electric energy.[1]

[1] This was the explanation accepted by most physicists at the time of writing; but it is doubtful whether it is now satisfactory. Dr Gustave Le Bon (*The Evolution of Forces*, 1908, Chap. II.) has pointed out that the apparently unlimited production of electrical energy in the induced body bears no relation to the strictly limited quantity of the charge on the inductor, and must therefore have some other source. The same reasoning applies to magnetic as to electric induction. His explanation is that electricity is the result of the dissociation of matter and that the disintegration of the atom sets free an enormous amount of intra-atomic energy. This view is now beginning to meet with acceptance. (*Cf.* P. D. Innes, *Proc. Roy. Soc.*, vol. lxxix., No. A, 532 p. 443.)

So far we have considered only the case when the magnet is bar-shaped, in which case the lines of force are distributed symmetrically on both sides in the field, or, in other words, the lines of force surround the magnet uniformly. Moreover, we used as the conductor in which the inductive action took place, a wire coil, and a movement parallel to the axis of the magnet followed, the extension of which went almost through the middle of the ring.

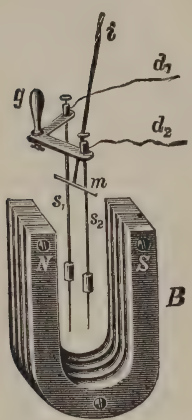


FIG. 145.—Demonstration of the induction currents (Grimsehl and Szymanski), $\frac{1}{10}$ natural size).

Here you see a strong horse-shoe magnet, composed of several steel plates or lamina (fig. 145).

As the conductor in which the induction acts we have a piece of brass rod (*m*, fig. 145), fastened to a long, insulating handle (*i*) and sliding upon the guide rods (s_1 s_2). These guide rods are fixed in a simple wooden frame (*g*) which permits of their simultaneous adjustment. From the rods two wires lead to the solenoid galvanometer (Appendix, 38, p. 410).

If I now hold the sliding rods (as shown in fig. 145) in the magnetic field, and move the conductor (*m*) down the rods quickly, so as to make good contact, we perceive a deflection on the galvanometer, which becomes greater in proportion to the number of lines of force cut, and is altogether absent if the movable conductor is pushed along the lines of force and hence does not cut through them.

If I bring a small magnet into the magnetic field, it arranges itself in alignment with the lines of force.

If now we call the direction to which the north-seeking pole of the needle points, while it is being led along the lines of force, the *direction of the lines of force*, we may state: *with the exception of a single line, which, for example, emerges when the bar magnet moves in the direction of the magnetic axis, all the lines of force form closed curves, which stretch from north pole to south pole in the air-space*, and, as we may imagine, *return from south pole to north pole inside the magnet.* If a magnet is moved, the entire system of lines of force is moved—that is, *the entire magnetic field moves with the magnet.* In this case, therefore, an induction current must be formed in a fixed conductor placed in a magnetic field which cuts through the lines of force. In the case of the rectilinear movement of the magnet, we have already seen this (p. 340). Direction of the lines of force.

For memorizing the direction of the induction current in the conductor acted upon inductively, a *memoria technica* has been invented: *Let a man imagine himself swimming in the direction of the lines of force, with his face turned towards the movement of the conductor, then the induction current flows towards his right* (Faraday). By analogy with Ampère's modified swimming rule for the deviation of the magnetic needle (p. 230), there is another version of the rule for the induction current (A. Fleming). Hold the forefinger, middle finger, and thumb of the *right* hand almost perpendicular to each other, and point the *first finger in the direction of the lines of force* (so that the tip of the finger shows where the north pole of magnet needle would point), and *the thumb in the direction of the intended movement of* Faraday's rule. Hand rule.

the conductor, then the MIDDLE *finger indicates the direction of the induction current in the conductor.*[1]

Let us hold over the horse-shoe magnet (first upright and then on its side) a piece of cardboard and iron filings; then you will see that the lines of force are most dense between the two poles, and least so at the outer sides of the legs.

Let us experiment with the movable couductor (fig. 145, p. 342) at several points of the magnetic field. We find that the induction current grows stronger at those places between the legs of the magnet where the lines of force are most dense—that is, where more lines of force are bisected by the conductor.

In the experiment on p. 337 we saw that an increase of the strength of the poles of the electromagnet, and hence an intensifying of the magnetic field, also strengthened the induction.

Review. Let us now put together what we have learnt:—

(1) *An induction current always arises if a conductor or a part of one cuts straight across a magnetic field*, and this whether the conductor moves in a stationary magnetic field or remains stationary while the magnetic field moves, or the intensity of the magnetic field is changed by a change of the strength of the poles of the electro-magnet.

(2) The electromotive force of the induction current generated in the conductor under otherwise equal conditions is proportional to:

[1] Better: Let the forefinger of the right hand point in the direction of the magnetic lines of force, then turn the thumb in the direction of the movement of the conductor: the middle finger, bent at right angles to both thumb and forefinger, will show the direction of the induced electromotive force.—*Ed.*

(*a*) The intensity of the magnetic field and therefore to the strength of the poles,
(*b*) The length of the conductor in which the induction acts, since the longer it is the more lines of force are cut,
(*c*) The velocity of movement of the conductor or of the magnetic field, because then also more lines of force are simultaneously bisected.

Having now learned the principles of magneto-electric induction, we can proceed to make ourselves acquainted with the practical applications thereof.

I. A magnetic needle hanging by a thread oscillates for some time after I have given it a slight push. I hold it just over the thick copper plate on the table (A, fig. 146), and you see that the needle, after a few oscillations, regains its equilibrium. During the movement of the needle, and hence of the magnetic field, induction currents are evoked, which (according to Lenz's law) strive to impart to the magnet an opposite direction, and, therefore, *damp* its oscillations.

Damping of the galvanometer needle by induction currents.

The needle of the very delicate magnetic needle galvanometer formerly used was enclosed in a case of very thick and pure copper, in order to "damp" the oscillations of the magnetic needle by the counter-action of the induction current. If the workmanship is good, a needle mounted in this manner takes up its position without oscillation (dead-beat galvanometer).

II. As a single coil of wire through which an electric current flows has already a magnetic directing force, and, therefore, produces an electric field, every turn of a solenoid must be in the magnetic field of the turn nearest to it; accordingly, every turn of a solenoid

must exercise an inductive effect upon the others, during the time *in which the current intensity changes*, *e.g.* at the making and breaking of the current flowing through.

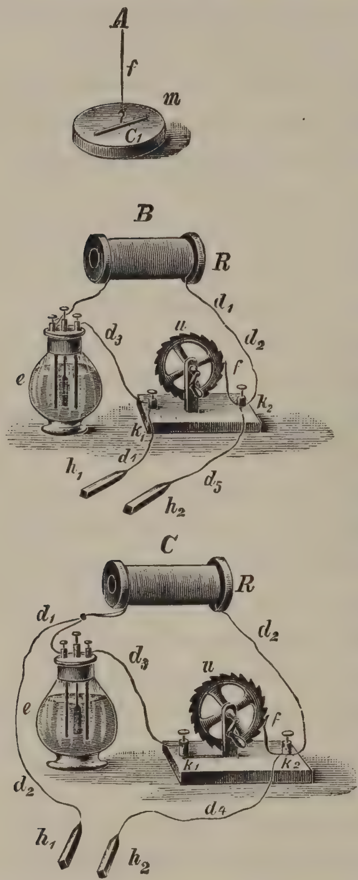


FIG. 146.—A, induction in a copper plate, $\frac{1}{10}$ natural size; B, C, self-induction in a coil of wire (extra current), $\frac{1}{10}$ natural size.

Thirty turns of insulated copper wire (B, fig. 146), rolled round a hollow cylinder, are connected with a cell (*e*) and a current interrupter (*u*). The latter, consisting of a copper-toothed wheel, the teeth of which are touched by a spring (*f*), is turned by a handle. Also two wires (d_4 d_5) leading from the terminals are provided with two brass handles, which I beg you to take hold of. Now I turn the wheel. Your hands tremble, and the trembling becomes greater the faster I turn, *i.e.* the quicker the shocks follow each other. Still stronger and even painful are the shocks if I push into the hollow of the bobbin (R) a bundle of soft iron wires. Now I will turn the toothed wheel slowly—the circuit is closed. You feel scarcely anything, and while the cell current flows through your body, nothing at all.

Now the spring slips from the wheel and the current is opened. You shrink!

Since the lines of force emanating when the current is closed cut the turns of wire of the bobbin, then, according to Lenz's law, an induction current is formed, of opposite direction to the main current. But when the current is interrupted, the lines of force (according to Faraday) are withdrawn, and hence the induction current is now in alignment with the main current, and must strengthen its physiological action.

We can also observe the induction current in itself, if we arrange the wires so that, when the main current is broken, the cell will *be out of circuit.* Such an arrangement is shown in C, fig. 146. If you grasp the handle, when the circuit is opened, only the induction current passes through your body. This current, which is only produced by the self-induction of the turns of a conductor on each other, is called by Faraday "extra current."[1]

Extra current.

On closing the main current, the extra current is opposed to it and weakens it; accordingly the main current can only gradually attain its full strength. When the main current is interrupted, the extra current is of short duration, and therefore of greater intensity.

[1] Every wire coil, through which a galvanic current passes, exhibits magnetic action and self-induction, from which disturbing side effects (*e.g.* in a galvanometer, or with reference to the resistance of the wire affected) may arise. In order to neutralize almost entirely this inductive action, the insulated wires connecting with the galvanometer are wound round each other (*cf.* fig. 111, C, p. 239), or, as in the case of the rheostat (fig. 126, p. 278), they are bent in the middle and then doubled and wound round a bobbin, and so the current has, in two conductors quite close to each other, an opposite direction. The self-induction is thus almost entirely stopped (inductionless winding).

III. Still stronger than the extra current is the induction current in a second wire coil, which surrounds the primary one (II, A, fig. 147), but without touching it. This secondary coil consists

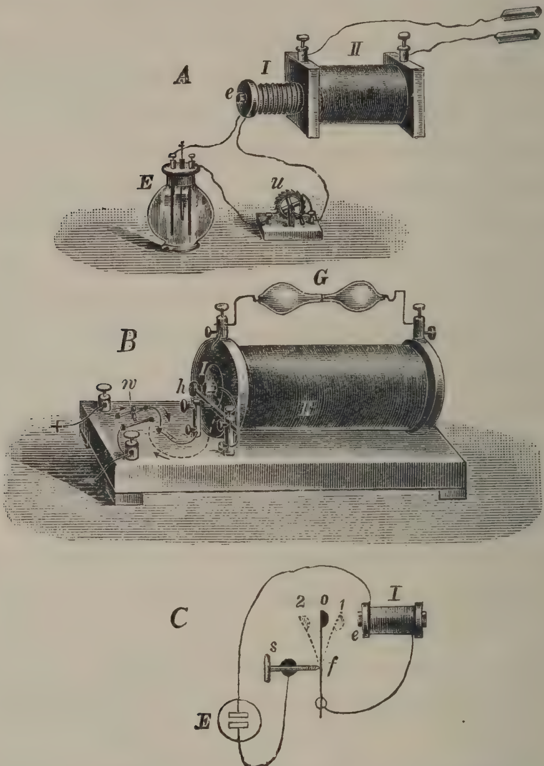


Fig. 147.—A, induction coil, $\frac{1}{10}$ natural size ; B, Rühmkorff's coil, $\frac{1}{12}$ natural size ; C, Wagner's hammer.

of many turns of fine insulated copper wire (about 0·15 mm. thick and several hundred metres long). At the closing of the main circuit, in every turn of the wire of the secondary coil an induction current of certain electromotive force is generated. As the turns are arranged in series, the total electromotive

force of the induction current is very great, and much greater than that of the primary coil. On the other hand, on account of the great resistance of the long fine wire, *the current intensity of the secondary coil is very small.* In a secondary coil of many turns, a transformation of an electric current of proportionately larger intensity and smaller electromotive force into an induction current of less intensity, but very great electromotive force, takes place, which in the case of large induction apparatus (B, fig. 147) assumes the character of the stream of sparks of an influence machine, except that it is more abundant.

The induction coil (II, A, fig. 147) gives painful shocks if the handles are grasped while the inducing current in the primary coil (I) is quickly closed and opened, especially if a bundle of iron wires is placed in its interior, by which the intensity of the magnetic field is much strengthened.

Rühmkorff's coil.

Still more forcible is the effect with a Rühmkorff's coil (B, fig. 147). Its primary coil is formed of sixty turns of strong copper wire, while the secondary coil has thousands of turns of very fine wire, some kilometres long. Of course this wire is silk-covered and also varnished; for otherwise, on account of the great polar difference, the sparks might burst through the insulating medium. In connection with the primary coil there is a commutator (w) and an automatic current interrupter, Wagner's electro-magnetic hammer (C, fig. 147). The current from the cell (E) flows to the commutator and traverses the primary coil (I); thence it runs to a brass spring (f), pressing against a screw (s), the points of contact being covered with platinum. At the free end of this spring is a

small iron plate, and its distance from the bundle of soft iron rods in the primary coil is regulated by the screw (*s*). If the circuit is closed, the iron is magnetized and attracts the plate. The spring (*f*) is drawn away from the contact screw (*s*), so that the circuit is broken and the hammer falls back again. The continual movement of the hammer is caused as follows: when at rest (*o* in C, fig. 147) the hammer touches the screw, the circuit is closed, and it increases to its full strength until the extra current is overcome, when it pulls away the hammer from the screw. The spring now is in position (1). While it remains thus the extra current (after interruption) acts for a time in the same direction as the primary and strains the spring still more. After returning to rest (*o*), when the circuit is again closed, the extra current acts contrary to the primary one, so that the oscillation of the spring (in position 2) is greater than if the primary current were to exert its full strength at one and the same time. The spring thus receives a small increase of velocity, which maintains the oscillation, just as in the case of a clock the impulse of the toothed wheel supplies the loss caused by the friction of the pendulum. This kind of electromagnetic current interrupter is used in the construction of electric bells.

Since the extra current of the primary coil weakens the inducing current at the closing of the circuit, and, so to say, reverberates when it is broken, so also does it weaken or hinder the induction current in the secondary coil. In order to lessen the effect of this extra current as much as possible in the large induction apparatus, *a condenser* is fitted in the hollow

stand. It consists of tinfoil insulated by mica plates, varnished or boiled in paraffin. The even and the odd leaves respectively are joined together and connected with the ends of the primary coil. When the circuit is broken, the primary coil is therefore closed by the condenser, the capacity of which is sufficient to hold the greater part of the extra current, so that, by the employment of a condenser, the spark, at breaking contact, between contact screw and spring is much smaller, and the spring must be at first pushed to set it vibrating.

By using this Wagner's hammer the current breaking may become so frequent that the hammering stroke of the hammer yields a particular high note.[1] The shocks which this induction apparatus give are, if not dangerous to life, still very unpleasant. If I screw on to the terminals of the secondary spiral wires provided with sealing-wax handles, and bring the ends near, you see, when the apparatus is in action, sparks of several centimetres long. Now I connect the wires with a glass tube, with platinum wires fused in the ends, and filled with a highly rarefied gas (Geissler's tubes, G; fig. 147, B). If we darken the room, a gentle glow emanates from the tubes, at the same time changing its colour, which depends on the nature of the gas. Some parts of the tubes consist of the yellow uranium glass, which sends forth a brilliant green light. Still more beautiful effects are given by Puluj's tubes, in which the rarefying of the air is carried to

Geissler's tubes.

[1] In recent times powerful induction apparatus has been constructed (length of spark 100 cm. and more), which allows of a very large number of interruptions (with Wehnelt's electrolyte current breaker, for instance, 1200–1700 breaks per second).

a greater extent, and fused gems glow in glorious colours. Rubies (even very common specimens) give forth magnificent rays of ruby light, diamonds mostly green.

Röntgen's tubes.

Of particular interest are Röntgen's tubes, to be seen nowadays everywhere. If these are connected in a suitable way with the poles of a powerful induction coil, having a spark length of 10–15 cm., from one of the platinum plates opposite to the kathode, called the "anti-kathode," the X-rays stream forth, which, though invisible to the eye, can pierce through most bodies, otherwise opaque, and excite fluorescence on a screen brushed over with platinocyanide of barium (Röntgen, 1895).[1] If you hold your hand between the Röntgen tube and the screen, we see on the back of the screen turned to us and coated with platinocyanide of barium a sharply defined shadow of its bony skeleton, surrounded by a fainter one of the muscles and the skin. If we move the fingers so as to cast shadows, we see distinctly the movement of the bones in their sockets. As the metals (especially lead) throw darker shadows than bones, foreign metallic bodies can easily be detected. Therefore the Röntgen rays (as they are called, after their discoverer) are now of much importance in surgery, and in the future will be much employed in testing materials of all kinds.

Since the Röntgen rays affect photographic plates, the figures thrown on the fluorescent screen may be fixed as photographs.

A highly interesting quality of the Röntgen rays is

[1] The fluorescence appearing on the side of the tube is an accessory phenomenon.

that they can discharge an electrified electroscope at a distance of 1–3 m., as they make the *air* through which they pass *conductive*. This process is called "Ionization" (see Appendix, 41, p. 413).

When experimenting with the induction apparatus, we sent the inducing current through the coil, which had only a few turns of copper wire, and obtained in the secondary coil induction currents of high potential, but of less current intensity. Let us transpose the two coils, *i.e.* let us send through the coil with the many turns [the secondary] the primary current. Then there arises in the other coil also an induction current with an electromotive force considerably smaller, but with a current intensity greater in proportion to the primary current. We are therefore able to transform currents of high potential into currents of less electromotive force but of greater intensity. Apparatus of this kind are called transformers. Of course the turns of wire must be well insulated. In practical use these transformers are of much importance. Transformers.

In induction apparatus and transformers the induction current in the stationary conductors and magnets arises from the intensification of the magnetic field, as the lines of force appear and vanish. But we can also produce them by moving the magnetic field, or by moving a conductor in a stationary magnetic field.

IV. Scarcely more than a year after Faraday's discovery of magneto-electric induction, Pixii (1832) constructed the first "magneto-electric machine." He caused a horse-shoe magnet to revolve before the

legs of a horse-shoe armature which were wrapped round with copper wire. In more recent apparatus, the iron core with wire coils is made to revolve before fixed horse-shoe magnets, which is much more convenient.

In the middle of last century, the magneto-electric machines of Stöhrer formed the show objects of the laboratory ; now they have been entirely superseded by their younger sister, the dynamo-electric machine (or, shortly, *dynamo*), and are merely of historical interest.

The enormous force of electro-magnets gave to Wilde of Manchester in 1866 the idea of making use of them instead of steel magnets in electro-magnetic machines. The well-known electrician Werner Siemens (1866) took the decisive step in the construction of the dynamo,[1] by showing that the magnetism remaining (or induced by the earth) in an electro-magnet was sufficient to generate in the turns of the rotating armature an induction current. This being led in a particular way through the turns of the electro-magnet raises its magnetism with great velocity, so that the induction current is greatly strengthened, which again is of advantage to the magnet, until the limit of its magnetization is attained without the addition of any external current. In this way the electro-magnet, after a certain number of rotations of the armature, is strong enough to send a

[1] Here the word "dynamo" (*dynamis* or force) denotes a machine in which nearly all the mechanical force (properly speaking "work") expended in moving the induction coils in a magnetic field generates current. But this is also the case with magneto-electric machines. The division into magneto-electric machines and dynamos is therefore conventional and has no practical meaning.

powerful branch current through the conducting mains (Siemens' dynamo-electric principle).

It is of the greatest importance to give to all these machines, both to the electro-magnet and armature which bears the induction coil, such a form that at every revolution as many lines of force as possible may be cut at right angles. Hence you see how necessary is a thorough knowledge of the path of the lines of force for the construction of good dynamos.

The main object in practice is to concentrate the lines of force as densely as possible in that part of the magnetic field already utilized, and to cut them all at right angles by the rotating conductor. The first is attained by using what are called pole-pieces, consisting of pieces of soft iron of a particular shape, which are fitted to the poles of the electro-magnet, or sometimes form an elongation of the pole. These have the property of inducing between their opposed faces a nearly uniform magnetic field of densely packed lines of force (A, fig. 148, p. 356).

A piece of soft iron, which is introduced into a magnetic field (B, fig. 148), has also, as a comparison of I and II will prove, the peculiarity of concentrating on itself the lines of force, and in a certain way of assimilating them. Hence the extraordinary intensification of the action of an induction coil by the introduction of an iron core.

Circular armature.

Of great interest is now the case when a ring of soft iron, or a hollow cylinder, the transverse section of which is a ring, is placed in the magnetic field between the pole-pieces (C, fig. 148). Calculation (Stefan, 1882), confirmed by experiment, proves that the lines of force (with the exception of the

middle one striking it perpendicularly) do not make for the hollow space in the middle of the ring, but pass along the substance of the ring and appear again at the other side. If a ring of this kind is spun on an axis, which in C, fig. 148, goes through the centre of the ring and is at right angles to its plane, the induced magnetic poles (n and s) of the ring remain

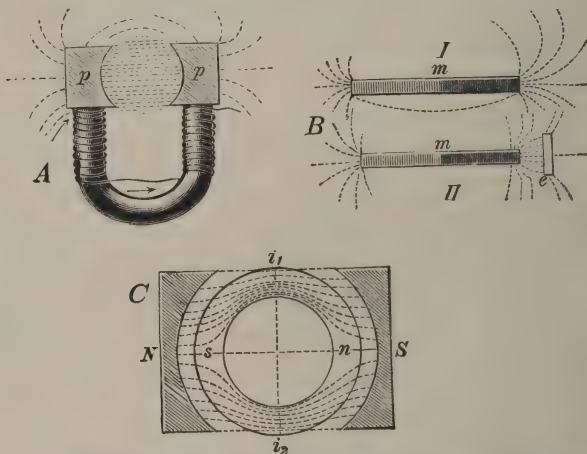


FIG. 148.—Diagram showing the course of lines of force. A, with pole-pieces; B I, in a free bar magnet; B II, in the presence of soft iron in a magnetic field; C, in a circle (cylinder) of soft iron between the pole-pieces. (From Stephan.)

in spite of the rotation in their former places in space, but are displaced in the rotating ring.

If now we wrap loosely round the iron ring a few turns of insulated copper wires, the ends of which are soldered together (A, fig. 149), then we can turn the ring with the wire coil round an axis perpendicular to the paper, or push the coil along the ring. Imagine the iron ring cut in two at the poles, and the action would not be affected, but we should have, as in an earlier experiment (VII, fig. 144), two (in this

case semi-circular) magnets, which are adjacent to the like poles, and the indifference points of which are at i_1 and i_2. Now we know that when a wire coil is run along a magnet with several successive points (p. 340), the induction current in the conductor is zero and its direction changes as soon as an indifference point is passed.

Let us observe the case referred to. While the wire coil is pushed from i_1 through s to i_2, an induced current develops which quickly increases at first and after passing the pole decreases; this at i_2 (as at i_1) $= 0$; its direction changes and its intensity increases and then decreases again until it again $= 0$ at i_1. The maximum current intensity is at the poles, because the dense lines of force entering these are cut at right angles by the conductor, while at the indifference points the conductor is pushed up parallel to the lines of force.

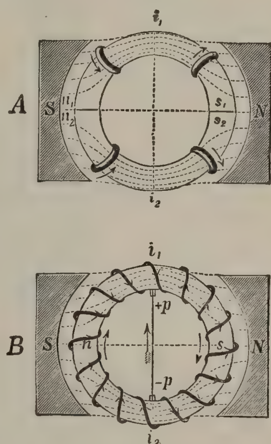


Fig. 149.—Diagram of Pacinotti's ring.

If we wrap the iron ring round with insulated copper wire, so that a closed wire conductor is formed (B, fig. 149), and cause it to rotate in a direction opposite to that in which it did before, then induction currents will be generated in the turns of the direction indicated by the little arrow heads.

A continual current of electricity flows in both semi-circles from the point i_1 to the opposite point i_2. If we connect these points i_1 and i_2 by means of a copper wire, the ends of which are drawn out into

brushes ($+p$ and $-p$), which press on the exposed parts of the winding wire, then an electric current of uniform direction is developed from i_2 to i_1 (B, fig. 149), and therefore from $+p$ to $-p$, and lasts as long as the armed wire ring rotates. If wires are led from

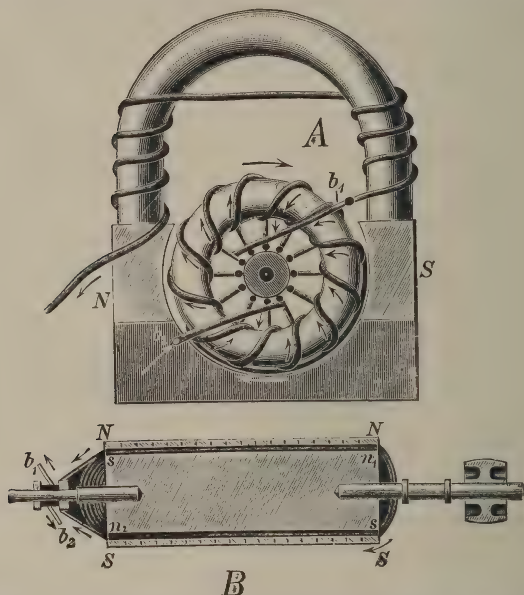


FIG. 150.—A, Pacinotti-Gramme ring (model after Weinhold), $\frac{1}{12}$ natural size ; B, Hefner-Altenecks' drum inductor—in section.

the windings to copper strips, which, insulated from one another, are fixed on the turning axis of the ring (A, fig. 150), and if the wire brushes touch at the right place, then at every moment parts of the wire coils, just as they pass by the indifference zones (i_1 i_2, B, fig. 149), will be in contact with the contact brushes. If conduction is established between both contact brushes (b_1 and b_2, A, fig. 150), then they are traversed by continuous currents flowing in the same

direction. In true Gramme machines, instead of each single winding of the ring armature, we must imagine a wire coil. The mode of action is, however, the same (Appendix, 38, p. 410).

The action of the inducing magnet pole, the so-called "field magnet," on the wire coils and that of the generated current in the coils of the armature has not been taken into account. Really the outside of the iron ring opposite the field magnetic pole is very dissimilarly, but the inside of the ring very weakly similarly magnetic, so that the process is more complicated. The total action, however, corresponds to our description; but for every machine of this nature the position of the contact brushes upon the insulated metal strips of the axis, which collect the induction currents and are hence called *collectors*, or (in this case wrongly) commutators, must be got by trial.

The first electro-magnetic machine which delivered continuous direct and induction currents was discovered by Professor Pacinotti of Pisa (1860), but his machine remained unnoticed and forgotten until the Belgian Gramme (1871) discovered it anew and improved it so much that it became of industrial use, and it then drove all other magneto-electric machines out of the field. For the solid iron core of the rotating ring he substituted a bundle of thin iron wires insulated from each other, as being capable of more rapid magnetization and demagnetization, and by this contrivance disturbing induction currents inside the core of the induction coil were also avoided. Only later did Pacinotti's inventions become known, so that the most essential part of this rotating machine, the rotating ring wrapped

with wire, is usually called Gramme's ring. These machines were soon constructed on the basis of Siemens' dynamo, and even now belong to the most powerful class of dynamos.

The drum inductor of Hefner-Alteneck, of the firm of Siemens and Halske in Berlin, which delivers direct continuous currents at will, rests on another principle. In this case the wire of the induction coil is rolled *lengthwise* round a soft iron cylinder, rotating immediately in front of the pole-pieces (NN, SS) of the field magnets, which embrace the greater part of the cover of the cylinder. Since, in this pattern of machine, the lines of force cut at right angles the greater part of the induction coil, very strong currents are formed. We cannot enter into a description of the very complicated action of this apparatus and the peculiar connection of the separate windings with one another and with the collector. Lately many new machines have been constructed, according to the particular requirements and ideas of their makers, but in the main they follow one of the types described: namely, Gramme's ring or Hefner-Alteneck's drum.

We must now examine the practical application of the principle of the dynamo, *i.e.* how the induction current is conducted through the windings of the field magnets, as the useful effect of the machine chiefly depends upon it.

I. The normal or *series winding* (I, fig. 151), first employed by Siemens in 1866, conducts the induction current through the spirals of the field magnet and then through the service conductor (BL), which is also in series. The induction currents can, in fact,

only arise in this place if the circuit is closed by the service conductor. This arrangement, which yields very strong currents when the resistance of the conductor (BL) is very small, has the disadvantage that when the resistance increases, the strength of current and therewith the force of the field magnet declines, which in its turn results in a further weakening of the induction current. Also a change of poles easily intervenes, which in certain kinds of work, such as electro-metallurgy, is very troublesome.

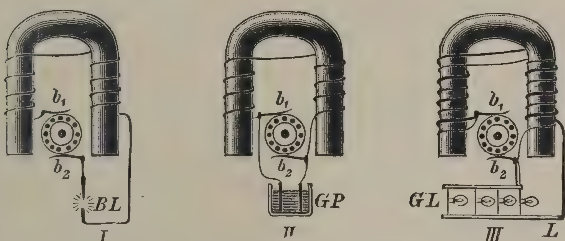


FIG. 151.—Various windings in dynamo. I, normal series; II, shunt winding; III, compound winding.

II. Shunt winding (II, fig. 151), which Wheatstone proposed in 1867, brings forth, from the brushes of the collector (b_1 b_2), a double current as service conductor. If this is now disconnected, the entire current flows round the field magnet. Also, if the resistance of the conducting medium is increased by the strengthening of the field magnet—the resistance of the coils of which remains unchanged, and, therefore, in comparison with that of the service conductor becomes smaller, and consequently contains a larger part of the current—the entire strength of current is still greater, as it would be according to Ohm's law when the current is constant—as for example with an electromagnetic machine. This winding is, compared with

the normal arrangement, especially advantageous if the service conductor has no constant resistance.

III. Compound winding, or connection with mixed windings, which was first used by Brush in 1879. The field magnet has in this case two windings. One, of strong wire, is connected, as the series winding, by the collector with the service conductor (L), whilst the other, of fine wire, only leads the current round the electro-magnet. When the resistance in the service conductor is increased, a correspondingly greater portion of current flows through the many coils of the thin wire, whereby the magnetic field and, with it, the total strength of current is so considerably increased that a machine of this kind (with compound winding), even when the resistance of the service conductor varies within wide limits, still exhibits a very constant electric polar difference.[1] It is, therefore, particularly suitable for electric lighting by means of incandescent lamps, which are not all in use at the same time. All dynamos give the best results when the resistance in the service conductor is equal to that in the windings of the machine. This latter corresponds to the internal, the former to the external resistance of the battery of galvanic cells.

The wonderful uses to which electricity has within the last few years been put are on the whole known

[1] In many works on electricity (especially those of a technical nature) the word *tension* is much used for electromotive force, or tension of poles and terminal voltage, instead of our expression "electric polar difference." I have avoided these expressions, as they may lead to misunderstandings. In these last cases, electric tension is not the same as "polar difference," or its equivalent "potential difference," which is meant here.

to you, so that I need only very shortly touch upon them.

The electric lighting of streets and lighthouses is effected by arc lamps. Here hard carbon rods are brought into contact by automatic contrivances, when the current is established, and having begun to glow, the ends are again drawn apart and kept at a certain distance. Since the direct current causes the positive carbon rod to be more quickly consumed, a thicker carbon is used, or a special dynamo is used with the alternating current (Appendix, 39, p. 411).

There are no limits to the illuminating power of the electric arc lamp, for lately masses of light have been generated which, taking distance into consideration, give more light than the sun.

The arc lamp, fitted with powerful parabolic reflectors and condensers, is of great importance to war-ships and armies in the field. It is very rich in the powerful blue and violet rays, and can therefore be used in photography. *Incandescent lamps* (p. 300), are used in the illuminating of rooms, as the light given, although of orange-gold shade, is softer and pleasanter for the eyes than the bright and dazzling arc lamp. Nernst's incandescent lamps do not need a vacuum and furnish a very beautiful white light.

The enormous heat of the electric arc light is the greatest which can be attained. By certain contrivances metals fixed at the point of contact can be melted and fused together. Benardos of St Petersburg was the first to carry out this operation. At the last Electrical Exhibition in St Petersburg cracked bells were fused in this way, and again made perfectly resonant.

Electric furnace.

The most stubborn acid combinations are decomposed by the heat of the electric arc, and by means of Siemens' electric furnace, out of common minerals such as clay, certain light metals can be extracted, as, for example, aluminium, pure or in alloys, as bronze.

Electric motors.

If one dynamo is properly connected with a second one, called the "inductor," then, if the first is put in action, the second or "*coupled*" one will rotate, as was the case with the influence machines (p. 119). If the axle of the inductor is provided with a fly wheel, then this "electric motor" will perform mechanical work, as if driven by a steam-engine. As it is not necessary for the driving machine to be directly coupled with the motor, but they may be connected by long conductors, the possibility arises of making use of certain forces of nature, which otherwise would be lost. If, for example, turbines are set up near waterfalls, and dynamos are driven by them, then the current can be led hundreds of miles uphill where such motive power is needed. In such transmissions of electric energy, transformers are of the utmost importance. As you already know (p. 256), the resistance of a long conductor is overcome with greater ease if the electromotive force of the current is very great. On the other hand, it is very difficult to insulate current of high potential, so that loss of energy easily takes place and may sometimes cause great damage by fire. It is also the case that if the conductor is accidentally touched, great danger to life results from the electric shock (Appendix, 39). Hence alternating induction currents of high potential (of 30 to 40,000 volts) are generated, which are

changed at their destination by transformers into currents of low potential (110 to 300 volts), but of correspondingly greater intensity, before they are transferred into the conducting mains. Since Doliwo-Dobrowolsky, at the Frankfort Exhibition in 1891, first carried the transmission of electric energy 175 kilometres from the Neckar, many factories have been built in Switzerland and driven in this way, and in North America entire towns are thus lighted. As our forests are becoming fewer and our coal-supplies, formerly considered to be inexhaustible, now threaten to give out, the transmission of electric energy is the problem of the future, and will certainly set its mark on the twentieth century.

The telephone.

Before closing the chapter on electric induction, I must mention one of its practical uses, at the same time one of the latest achievements of our age, and scarcely of less importance than the telegraph. I refer of course to the telephone, or "distance talker."

In 1860, Reis constructed a telephone, on the principle that a steel knitting-needle, wrapped round with copper wire, when made to vibrate rhythmically by current shocks, gives forth a clear sound, the pitch of which depends on the number of shocks per second. In Reis's contrivance the electric current was closed and then entirely opened, and when a sound was transmitted, the pitch was repeated but not the *timbre*. This defect, as well as the buzzing, annoying, subsidiary sounds it gave forth, caused this instrument to be relegated to the curiosity cupboard of the laboratory, whence it was only taken to serve as an amusement for the idle student.

Of more ingenious, simpler, and therefore better construction is Graham Bell's telephone of 1877, which, although in an altered form, will be known to most of you.

To make the *modus operandi* of the instrument more intelligible, I take a bar magnet (M, in fig. 152, A), fitted with an induction coil, the ends of which lead to our solenoid galvanometer[1] (fig. 130). A thin piece of sheet iron is fastened on a stand (*e*). When I put this near the magnet, the galvanometer deflects, but returns to 0 immediately the iron plate is at rest. When it is removed again, the needle deflects to the other side —that is to say, while an iron plate is approaching the pole of a magnet, an induction current is induced in the wire coil surrounding it. The same thing happens when the plate is being taken away; but the current is in this case in the opposite direction. If the sheet-iron plate is quite close to the magnet, a slight movement of it is enough to generate an induction current.

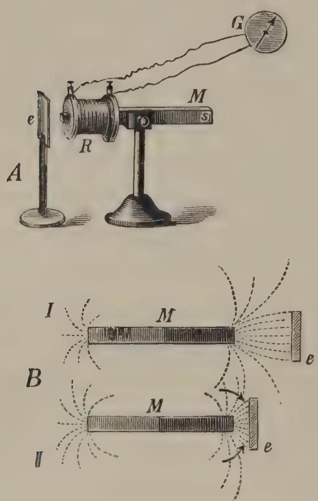


Fig. 152.—Action of the telephone, $\frac{1}{10}$ natural size. A, generation of an induction current by the approach of an iron plate to the core of an induction coil; B, displacement of the lines of force of a bar magnet on the approach of an iron plate.

As we know, an induction current only arises if a conductor cuts right across the magnetic lines of force.

[1] In fig. 152 a simple galvanometer only is shown.

But in this case both the induction coil and the magnet are at rest, and therefore the approaching (or the removing) of the iron plate must have acted as if the lines of force alone had been displaced, and in so doing had cut across the windings of the induction coil. We have seen (fig. 148, p. 356) that the presence of a piece of iron in the magnetic field influences the course of the lines of force. To show you the effect of the movement of the piece of iron upon the lines of force, I lay before you on the table a powerful bar magnet, cover it with a piece of cardboard, and indicate in the usual way with steel filings the magnetic lines of force. Whilst one of you, by knocking on the card, causes the movement, I push a piece of very soft iron, fastened to a long, thin wooden rod, towards the magnetic axis of one pole (B, fig. 152). You see how the lines of force turn more and more towards the piece of iron the nearer this last comes to the pole. Now (in B, fig. 152) the lines of force are already much denser at the magnetic poles than before, and it is just the opposite as the iron is withdrawn. The approach of an iron plate to the magnetic pole has the same effect as an increase of the intensity of the magnetic field in front of the poles, or as a concentration of the lines of force at the magnetic poles, and therefore a displacement in the direction of the arrows in II B, fig. 152. And this is the condition for the formation of induction currents (*cf.* pp. 334 and 341).

To make the mode of action of Bell's telephone clear to you, I will use a simple model (A, fig. 153). Two strong magnets on stands have at the end of each wire coils, which are connected with each other by

wires, so that the induction current induced in R_1 may act also in R_2. Before the pole of M_2 there swings by a fine elastic watch-spring a small thin disc of thin sheet iron (e), having a piece of paper gummed on the side turned towards the pole. I regulate the distance so that the spring may be somewhat stretched, owing to the attraction exercised upon the disc, but so that the *disc and the magnet do not*

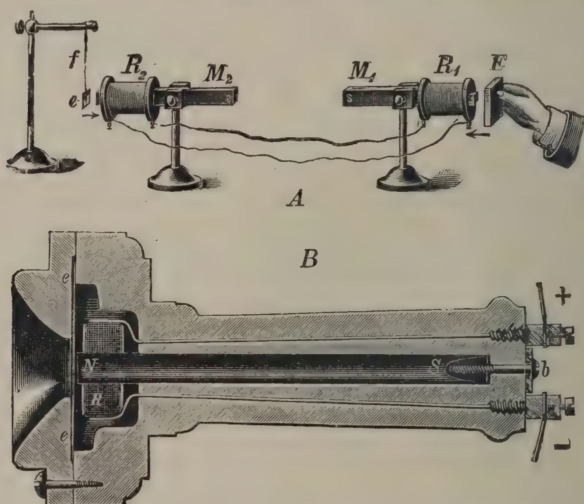


FIG. 153.—A, simple model of telephone, after Bosschard, $\frac{1}{10}$ natural size ; B, Bell's telephone, $\frac{1}{2}$ natural size.

touch. If I present a soft iron plate (E) quickly to the magnet M_1, the little disc (e) is at the same time attracted, although the movement can scarcely be noticed. But if, while the spring vibrates, I present and withdraw E, the disc (e) soon exhibits visible oscillations. If I had crossed the connecting wires or had put the wire coil in the nearer end of M_2, the oscillations of e would also have followed, but the inducing current would have influenced the intensity

of the magnetic field at M_2 in the *opposite* way, and therefore an approach of E to M_1 would have caused the withdrawal of the disc (e) from M_2.

Bell's telephone (B, fig. 153) consists only of a strongly magnetized steel rod which is at a very short distance, which can be adjusted by a screw, from a round nickelled plate of thin sheet iron (e). This, tightly fixed in the casing of the plate, is attracted by the magnet and, therefore, *kept continually in a state of tension.* But if, by reason of sound-waves, this iron membrane is set vibrating, then both by the approach and the immediate withdrawal of the plate from the pole, induction currents of the *opposite direction* are induced in the coil (R), which are conducted to a second telephone. In this, each separate current shock generates at the like intervals variations of intensity in the magnetic field, and the iron membrane of the second telephone is thrown into the same simultaneous or isochronous vibrations, which are imparted to the air and become audible as sounds.

In this process we have the following phases :—

I. *Telephone* (*Transmitter*).

1. The vibrations of sound produced in front of the telephone cause similar vibrations in the iron plate.
2. Hence arise oscillations in the intensity of the magnetic field.
3. These generate induction currents.

II. *Telephone* (*Receiver*).

4. The impact of the current generates oscillations in the intensity of the magnetic field.
5. This occasions vibrations in the iron plate,
6. Hence vibrations in the air are caused.

By means of Bell's telephone, therefore, without the aid of any source of current, a sound may be transmitted to another place, or, to put it more accurately, again called forth there. But since, in this case, the induction currents must first be pro-

duced by the vibrations of the iron membrane, and in addition there must be a conversion of mechanical energy into magnetic and electric energy (and *vice versa*), in which operation a loss of energy cannot be avoided, it follows that these telephones are only capable of conveying the human voice distinctly over comparatively short distances. Yet well-constructed instruments, particularly those of von Siemens of Berlin and of Ader in Paris, which have horse-shoe magnets with pole-pieces which act simultaneously on the plate, are strong enough to act over a distance of 30–40 km. [roughly, 18 to 25 miles], and hence are often employed in town telephone systems.

To telephone distinctly over greater distances, the oscillations in the intensity of the magnetic field must be increased, without, at the same time, interrupting the current entirely, as was the fault in Reis's instrument. The main thing is, then, instead of using up the energy of the sound waves, to draw upon *that* source of current supply, and by bringing about, by means of sound vibrations, an alternate to-and-fro variation in the current intensity, to reproduce, in the second apparatus, not only the pitch and the relative strength of simple tones, but also, as far as possible, their *timbre* or quality.

The microphone.

Lüdtge (of Berlin, January 1898), and at the same time Hughes, were successful in effecting this in a surprisingly simple manner. If pieces of charcoal, loosely put together, are connected in the circuit of a galvanic cell, they will give, when pressed closer, an extension of the contact surface, and with it a decrease of the resistance at the same place. If a carbon rod

(A, fig. 154) is placed between two fixed pieces of the same material (and connected with the conducting wires), so that the pressure may be regulated, then small shocks given to the diaphragm, to which the carbon-holders are connected, will cause a corresponding decrease or increase of the resistance, whereby

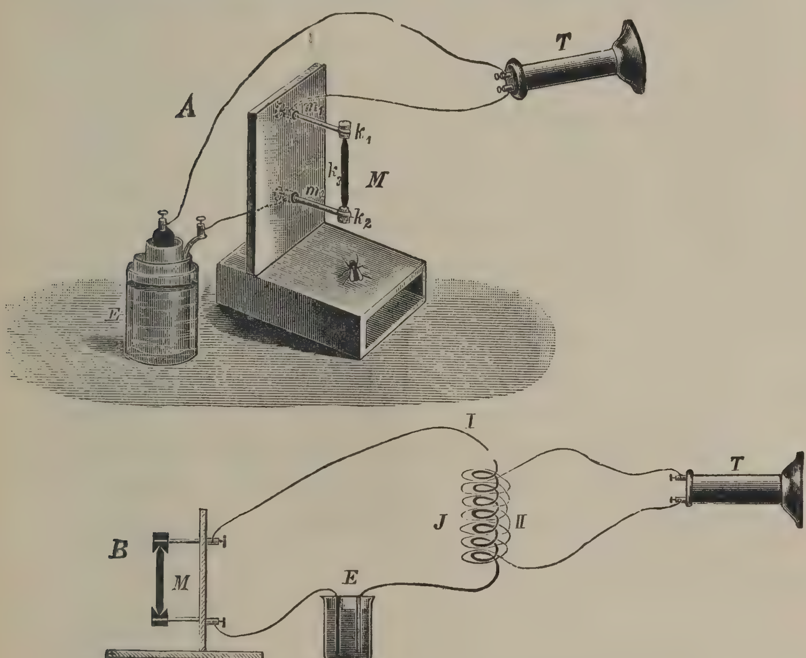


FIG. 154.—A, microphone, ⅛ natural size ; B, telephone (T) with microphone (M) and induction coil (J).

current undulations will be generated. These bring about in the telephone circuit much greater variations of the intensity of the magnetic field than the weak induction currents of a transmitting telephone. The tone is so much strengthened, that the crawling of a fly, for example, is heard as a loud scratching. By its means the smallest noise can be

heard, hence Hughes—by analogy with the microscope, which displays to our view the miniature world—called it a microphone or distance-hearer.

It becomes much more effective—especially if the sounds have to be conveyed very great distances—when used in conjunction with an induction apparatus (A, fig. 147). If the current is led from the microphone to the primary coil (I), thence back to the cell, and then to the secondary coil (II) consisting of many windings, induction currents of high potential will be generated by the vibrations caused by the microphone. These, in their turn, will act most energetically on the telephone connected with it, at a very great distance away. In this manner it has been possible to connect by telephone places so far apart as New York and Chicago; and even the sea offers no insuperable obstacles. Daily the telephone is drawing near to one another towns and even nations, so that it is a most important factor in everyday life. It has completed the work of its elder brother, the telegraph, by rendering it possible to recognise the very voice of the speaker.

Conclusion

I have occupied your attention in this chapter for a long time, yet I have been able to touch upon only the salient points, as otherwise we should overstep our proposed limits.

Often during our wanderings we have had to take refuge in *hypotheses*, in order to bring into line the phenomena observed. Perhaps it will not be uninteresting now, at the conclusion, to cast a backward

glance at the changes in these physical hypotheses, and then to cast one forward in the direction whither the investigators of to-day are bending their steps.[1]

One often sees in books the statement that the task of physics, as a science, is "to explain observed phenomena." What is the exact meaning of "explaining" physical processes? Evidently nothing more than to refer unknown processes to known ones, and it depends on the accidental evolution of physics as to what is to be considered as "*unknown.*" All explanations of physical processes, therefore, bear the mark of uncertainty, and are dependent upon the changes of the epoch. It is not the explanation of physical phenomena, but rather the demonstration of their connection, which is of lasting value, and which we require for the knowledge of nature. The object of physics, therefore, is to reveal the connection of all observed phenomena.

At the beginning of the present century it was universally accepted that heat, light, magnetism, and electricity were quite independent bodies or fluids, not subject to the law of gravitation, and hence without weight or imponderables. According to this notion, physics was divided into the science of the *ponderables,* the mechanics of solid, fluid, and gaseous bodies, and of the *imponderables*, four or six of which, namely, heat, light, magnetism, and electricity, were recognised, the last two being again subdivided by the supporters of the two-fluid theory into two substances with opposite qualities. There

[1] In this the author is following the thoughts of Prof. Dr. O. Chwolson, given in a small but fascinating pamphlet, "The Hertzian Experiments" (1890).

was no connection between these various domains. But when the influence which the galvanic current exerted upon the magnetic needle established an unexpected connection between the domains of electricity and magnetism, until then supposed to be wide apart, the barriers between the two fell to the ground, and there was no further ground for attributing any special and particular quality of imponderability to magnetism. Hence this theory was given up.

This was an important moment in the history of the development of physics, for natural science then entered upon a new phase. Similar results, not so marked, because already foreseen, followed researches in spectrum analysis, when it was proved that the rays of heat and of light, as also the chemically active rays, were not intrinsically different, but that it depends on the nature of the bodies on which it impinges whether the same ray causes heat, light, or chemical action. It was now generally accepted that these light and heat rays are simply one and the same; that is, they are all oscillatory movements of the all-pervading, imponderable matter called ether; and so the idea of a "heat-matter" was shelved. The latest theories then current only recognised two entirely distinct imponderables: the light-ether as a carrier of the phenomena of light and heat, and the entirely mysterious, incomprehensible bearer of electrical and magnetic phenomena.

Towards the end of last century physicists accepted the hypothesis that the phenomena of influence and induction were direct action at a distance, in which the "insulating" medium lying between a dielectric played a passive part, so that all electric processes

were confined to those taking place in or upon the conductor. Faraday would not accept the theory of action at a distance without a medium, and held that the dielectric surrounding an electric conductor was the main carrier of dynamic or kinetic action. According to him, the magnetic and electric lines of force which marked the direction of the forces working for the time being had a real existence. He proved by the condenser that the nature of the dielectric considerably influenced the capacity of the condenser; that, for example, a vacuum acted as a dielectric, and that the substitution for air of another dielectric, *e.g.* sulphur or gas, increased the capacity of the condenser in a particular ratio (p. 92). Hence he concluded that the magnetic and electrical dynamic effects take place in the surrounding dielectric itself, and that these changes of condition are made in this and not in the conductor, these changes being what we call electric actions at a distance. Faraday also supposed that these changes of condition took place indirectly; therefore they kept moving from point to point. It follows from this that the real causes of magneto-electric action must be some medium pervading all space, and that these actions, even in the dielectric, require time to spread from one point to another. It is even conceivable that this electric action in space still continues, although the exciting force which acted in the beginning has vanished; just as a planet may already be extinguished while we still see it in the heavens, because its light had been many years on the way before it meets our eye. Almost of necessity, therefore, the hypothesis gained followers that the

world-ether and the light-ether were at one and the same time carriers of magnetic and electric phenomena. Recent researches have made this highly probable. Faraday, the greatest experimentalist of all time, did not possess the equipment of the higher mathematics, but his pupil, Clerk-Maxwell, who unfortunately died before his master, drew up on a mathematical basis an electro-magnetic theory of light, which conceives magnetic, electric, and optical phenomena as reciprocal movements in the ether. If this theory is correct, magneto-electric undulations should be producible which obey the laws of optics, that is, should possess reflection and refraction. Neither Faraday nor Maxwell were able to bring their experiments to a successful issue on this point; in fact, it was not until the end of the nineteenth century that a young German scientist, who unfortunately died early (1st January 1894), Professor Heinrich Hertz, after arousing wide interest by his *Researches as to the Propagation of Electrical Energy*[1] among the physicists of all nations, placed himself by one stroke in the forefront of the scholars of all time, by the great discovery denied to the genius of his predecessors.

It is not my task to describe to you the complicated experiments of the talented physicist, in whom the experimental facility of a Faraday was joined to the mathematical precision of Maxwell. It will be sufficient if I point out a few of the difficulties that had to be overcome, and to mention shortly some of the results.

[1] *Untersuchungen über die Ausbreitung der elektrischen Kraft* (1887–1893).

The light-ether, like every other elastic medium, has the property of propagating, through periodic impacts in one spot, continuous concussions or perturbations of constant velocity which is quite independent of the number of impacts occurring per unit of time. In the wave movements of light, the separate particles have a kind of oscillating motion like that of a pendulum, while the propagation in space, at right angles to the plane of oscillation, of the separate particles is the result (transversal oscillation). The space round which the movement in space goes on, while a particle is completing its undulations to and fro about its point of equilibrium, is called its *wave length.* Since, as was mentioned, the velocity of propagation of the waves is constant, the waves will be longer in proportion to the slowness with which the periodic impacts which provoke them succeed each other. We now know that the magneto-electric waves, like light waves, consist of transverse oscillations of the ether, and hence they must have the same velocity of propagation as light—that is to say, 300,000 kilometres, or 300 million metres per second. Under these conditions electric waves of 10 metres long (longer ones can scarcely be observed in an enclosed space) must complete $\frac{300,000,000}{10}$ or 30 million oscillations per second. In order to generate waves of 3 metres long, capable of being observed in a physical laboratory, the generating impacts should follow each other 100 million times in one second.

After numerous failures, Hertz succeeded, by means of a clever contrivance which he fitted to a Rühmkorff's induction coil, in causing electric discharges to follow one another with such velocity as Hertz's electric waves.

to be able, with their help, to generate permanent "electric waves" in the air, the wave length of which could be measured. He also discovered that these electric waves are transmitted in straight lines in a uniform dielectric, but that if they meet another dielectric they are refracted like, and, in fact, according to the same laws as, the rays of light. Surprising, too, at first was it to find, although it was in agreement with Maxwell's theory, that *conductors* or metals do not transmit electric oscillations, but reflect them.

To give you at least a representation of the origin of electric waves, we will make use of a very simple, but at the same time a very effective arrangement.

The coherer.

The most essential part of this is the coherer (A, fig. 155), consisting of two powerfully magnetized steel rods (m_1 m_2), 2 mm. thick, the distance of which from each other may be accurately regulated by the micrometer screw (MS). The magnetic rods are fitted into small insulated, nickel-plated metal stands, which serve at once for the reception of the wires conducting the current and of the antenna (a). The function of this antenna is to intensify the electric waves, which it does by intercepting them and imparting their oscillations to the coherer. A similar phenomenon, called resonance, occurs in acoustics. Between the unlike magnetic poles, which are close together, there is a sprinkling of very fine, bright iron filings (e), which forms the bridge for the electric current E_1 E_2 (B, fig. 155). During the experiment a piece of cardboard is placed over the screw x to prevent the filings falling on the micrometer. Since the loose filings have only very small contact surfaces, their

electric resistance is so great, that the current of the cells E_1 E_2, in series, is only just able, when the distance between the poles is very great, to ring the bell and produce deflection of the galvanometer.[1]

Let us increase the distance between the poles

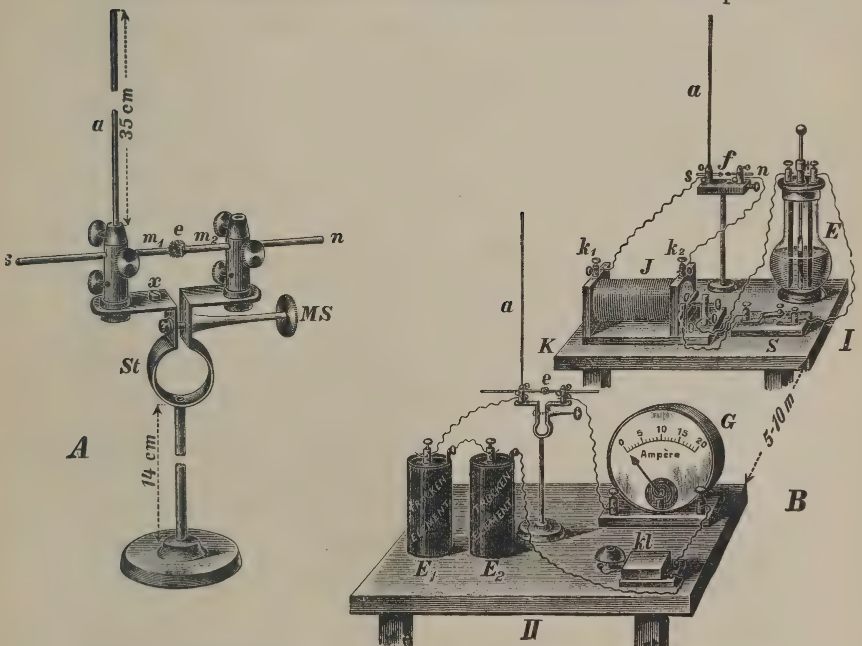


FIG. 155.—Electric waves (spark telegraphy). A, coherer (after Geschöser), improved by H. Pantenius, $\frac{1}{3}$ natural size; B, Experimental arrangement. I *e*, micrometer movable spark gap (transmitter); J, small induction coil; E, cell; S, switch key. II *e*, coherer (receiver); G, galvanometer; *kl*, electric bell, about $\frac{1}{10}$ natural size.

until the action just ceases. Now the receiving station (II B, fig. 155) is ready for use.

In the transmitting station (I B, fig. 155) the current of the cell E passes through the primary of

[1] The solenoid galvanometer (fig. 130) is very convenient, or the galvanoscope (C, fig. 111). In fig. 155 is shown a dead-beat galvanometer.

the small induction coil (J), and may be closed at will by the contact key (S). The secondary winding is also connected with the movable spark gap[1] with micrometer screw adjustment *f*, from the end of one of the supports of which rises a little brass rod connected with the antenna. This is, like the other, of copper wire, 350 mm. long and 2 mm. thick.

As soon as one of you presses down the contact key (S), the electric bell sounds and the galvanometer exhibits a great deflection. On account of the electric waves, the conductivity of the sprinkling of iron filings has suddenly become greater. By tapping on the coherer stand with a lead-pencil, or by striking on the table, the unstable equilibrium of the iron filings is again disturbed. The bell stops ringing and the galvanometer needle returns to its position at 0.

In the case of the coherers used for spark telegraphy, a contrivance similar to the striking lever of an electric bell is fitted, which automatically gives a shock to the coherer and makes it immediately capable of action again, as is necessary for telegraphic operations.

We cannot go further into this; still, I must just mention that if the coherer and the spark length are fixed in the focal point of a properly-shaped cylindrical parabolic reflector, the influence of the electric rays thrown in a certain direction is perceptible from a

[1] This contrivance may be dispensed with, if one does not mind the trouble of connecting the proper wires to the terminals of the secondary spiral (J). It is advisable to insulate the outer ends with handles of sealing wax or ebonite, and to bend them into loops, one of which is horizontal and the other vertical. By this means the spark length will be greater. The spark length must be in unison with the coherer. Here it $=0{\cdot}5$ to $0{\cdot}2$ mm.

great distance; thus the polarization, reflection, and refraction of the electric rays may be shown.

The great importance which wireless telegraphy has lately gained is well known to you. It has proved a boon to ships, and in future will be much employed in war both on land and sea.

It is of great interest to follow the progress of our knowledge in the domain of ether waves. Before I pass on to give you a glimpse of this matter, I should like to call your attention to the measurements used for calculating wave lengths.

You know that 1 kilometre (1 km) = 1000 metres, and 1 metre = 1000 mm. For very small magnitudes, as light waves, the millimetre even is too great. Therefore as unit of length the $\frac{1}{1000}$ part of a mm., *i.e.* 1 mikron (1 μ), and its thousandth part, 1 mikromikron (1 $\mu\mu$), were taken. Thus we have[1]

$$1 \text{ km.} = 1000 \text{ m.}$$
$$1 \text{ m.} = 1000 \text{ mm.}$$
$$1 \text{ mm.} = 1000\ \mu.$$
$$1\ \mu = 1000\ \mu\mu.$$

If we want to use a single one of these units of length as measure, we should have to deal with very large numbers, or with decimals of many places.

In acoustics, the interval between two tones, the higher of which makes exactly double as many vibrations or has a wave length half as great, is called "an octave."

[1] In scientific works it is the custom, for the sake of clearness, and to prevent the confusion arising from factors, to write the name of the unit of measure above as index—thus, $10^{\circ}\ 15'\ 16''$ $3^{h}\ 18^{m}\ 12^{s}$. For typographical reasons, objection is often taken to this.

If we use this method for the ether waves, then we have the lower octaves.

Fundamental.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
$\lambda=1$ m.	2 m.	4 m.	8 m.	16 m.	32 m.	64 m.	128 m.	256 m.	512 m.	1024 m.
							In round Nos. . .			1000 m.

If in octave X we put 1000 (instead of 1024), the error is $\frac{24}{1024}$: that is, 2·3 per cent. This makes it possible for us to replace every tenth octave by one of the above units of length, by which means a clear view of the whole range may be obtained.

The following fig. (156) shows you a diagram of the ether waves now known, which I have taken from Professor Dr P. Lebedeff of Moscow's "Skala des elektro-magnetischen Wellen des Äthers," *Physikalische Rundschan*, 1901, p. 229, which the author has kindly allowed me to reproduce here. He has also completed them by forwarding particulars of the wave lengths of spark telegraphy, and by corrections in the upper regions of the waves generated by alternating dynamos, as shown by the bolometer.

At first only the one octave of the rays visible to the eye, namely, the solar spectrum, was known; then the thermal and the chemical or photographic rays were examined. The entire range comprises more than nine octaves, six of which come below the less refrangible infra red, and a little more than two octaves above the ultra-violet rays.

How immensely our knowledge of ether vibrations was extended by Hertz's discovery will be seen by

a glance at the table (fig. 156). Hertz's waves in wires and in the air alone embrace sixteen octaves, and all those already observed more than thirty-two (Appendix, 18).

Between the shortest electric waves and the longest heat waves there still remains an *uninvestigated region*, but its exploration is merely a question of time.

It is otherwise with the unknown domain beyond the ultra-violet rays, and it is scarcely probable that we shall ever be able to identify waves, the length of which is smaller than the diameter of the molecule ($1\mu\mu$).

As Helmholtz showed, waves of

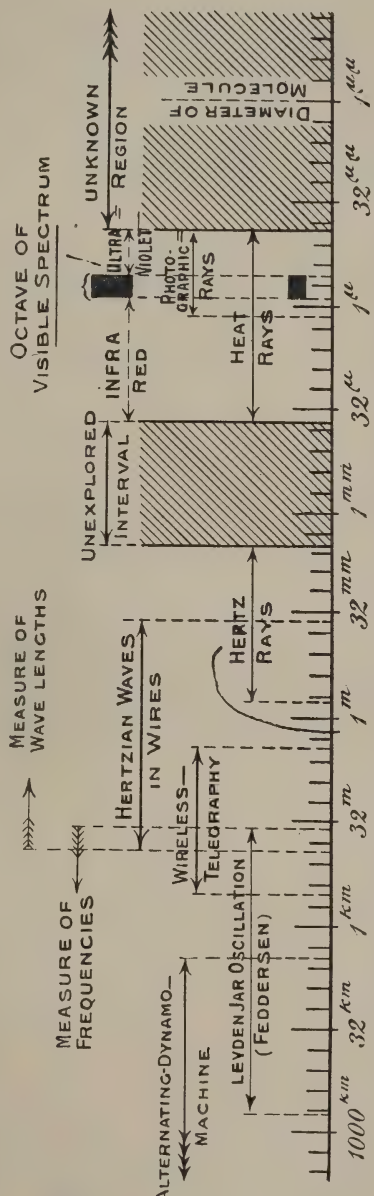


Fig. 156.—Scale of octaves of electro-magnetic ether-wave lengths, after Professor Dr P. Lebedeff, Moscow. [1 μ (mikron) $= \frac{1}{1000}$ mm.; 1 $\mu\mu$ (mikromikron) $= \frac{1}{1000}$ ($= \frac{1}{1,000,000}$ mm.).]

so small a length can exhibit scarcely any perceptible reflection and refraction, and hence their wave length cannot be calculated according to optical methods. The saying of Dubois-Reymond is very suitable in this connection: "Science has no eternal boundaries, but still there is always some boundary."

By Hertz's discovery, the theory resting upon Faraday's and Maxwell's electro-magnetic light hypothesis was confirmed, and now, about 100 years after the discovery of the galvanic current, the partition which divided optical from magneto - electric phenomena falls to the ground. There is still much to investigate, but through the preliminary researches of Faraday, Maxwell, and Hertz, the science of physics has entered upon a new phase of development.

I have only been able to give you an introduction to the science of electricity. But if you are induced by what you have learned, to make further incursions into its domain, my labours will be amply rewarded.

Appendix

HISTORICAL REMARKS—REPAIRS—SUPPLEMENTARY AND PRACTICAL HINTS

1. THE name "electricity"[1] (amber-force) was invented by Gilbert (b. 1540 at Colchester, d. 1603 at London). In his work, *De Magnete magneticisque corporibus et de magno magnete tellure Physiologia nova* (London, 1600), the following passage occurs: "Vim illam *electricam* nobis placet appellare, quæ ab humore pervenit." "We will call this force which comes from moisture, electric." Since this work contains the earliest researches in the science of electricity, a short time ago (1900) we celebrated the three hundredth anniversary of the real discovery of electricity. Page 1.

2. The first electroscope (Franklin's) consisted of two insulated flax threads, from the end of which two small balls of elder pith were later suspended (Canton). Saussure used two bits of straw and Bennet two strips of gold leaf, which has, in most cases, been replaced by an aluminium leaf. In all the electroscopes above described the movable parts are at the end of the conducting rod. Only in recent times were the leaves attached to the side of the rod, and the angle of divergence thus received a considerable increase (Exner). The paper electroscopes used by me work on a kind of hinge, as does my single leaf aluminium electrometer (*Zeitsch.* Page 7.

[1] Electrum was originally a natural alloy of gold and silver (the proportion of silver being more than 20 per cent.), of which, about the seventh century B.C., the early Lydian and Greek coinage was manufactured. The colour, a pale yellow, caused the Greeks to call amber also electrum.

für d. phys. und chem. Unter., 1888, p. 152, and 1889, p. 153). By this contrivance, the sensitiveness and the durability of the apparatus is much increased. It has lately had imitators.

Page 8. 3. *Mica* (also called Marienglas) is a mineral containing silicium and potassium. The dark variety of magnesium-mica is not suitable, because it contains an oxide of iron and so acts as a conductor. The potassium-mica can be split into the thinnest sheets, which, after being dried in the sun or over a flame, are excellent insulators. It is recommended, however, to give them a thin coating of shellac-varnish.

It is still better to cover the mica plates with a thin film of paraffin. They are laid on a heated sheet of metal and the paraffin is rubbed in with a ball of warmed hygroscopic cotton-wool, so that only the thinnest layer is left.

Pages 21, 22. 4. The flexible wire-gauze (fig. 9) was used more than thirty years ago by Professor Vanderfliet in his St Petersburg lectures. The model I have described is a modified and more convenient form of the instrument. It deserves a much wider use than it has hitherto had.

Page 26. 5. For this pretty experiment to be successful (fig. 12), the air must be allowed to enter slowly, otherwise the soap-bubble will easily burst. It is also advisable to clamp the ebonite tube to the short arm (at least 20 cm. long) of a retort-stand. For the soap-solution, Marseilles soap is the best; a drop of liquid ammonia and a few drops of glycerine may be added (rather too little than too much). The proper strength of the solution must be found by experiment.

Page 32. 6. *I.* The lamp here used (L, fig. 16) was a petroleum flat burner of 18 candle power; later I used an acetylene lamp. The condensing lens (k) has a diameter of 8 cm., and a focal length of 10·4 cm. The double lens (p), consisting of two plano-convex lenses, has a diameter of 10 cm. and a focal length of 15·5 cm. The distance between it and the projection screen (S) is, in a fully darkened room, 2·5 m., or 1·5 m. when the screen is placed near the side of the window, so that no direct light from the window falls on the side of the screen used. It is better to darken this window.

For the projection, a parabolic reflector of nickel plated metal

about 15 cm. high is placed on the lower part of the burner to concentrate the light of the lamp and to conceal the flame from the onlookers. In fig. 16 this is left out, as is the black screen (25×25 cm.) which is put on the frame of the lens (p) to protect the projection-screen from troublesome side lights. When electric light is available, instead of the lamp above described, an electric incandescent lamp of 25 (or, better, 50 candle power) is recommended. One-half of the bulb should be silvered. This is screwed into a socket and placed on a stand, and several such lamps should be provided. A socket fitted with flexible wire ($1\frac{1}{2}-2$m.) which can be used for any incandescent lamp is suitable. The contact fork at the end of the conducting wire need then only be inserted in the plug of the lamp-stand. It is as well for the incandescent lamp to be put inside a cardboard covering, with a hole (80 mm.) cut in the side. The screen should be placed opposite the darkened window and in such a position that no light from the other windows can spoil the effect (*cf.* note, p. 29).

II. More convenient than the projection table shown in the illustration is the improved projection table (fig. 158, p. 398). In this apparatus, the lamp and table-top with condenser and projection lens can be raised together or separately; a double condensing lens is also used (Focus 60–75 mm.). This projection table is very convenient for many projection experiments, as all the manipulations of the experimenter can be followed by the audience.

7. Coulomb discovered the laws of electrical repulsion by means of his torsion-balance, which is now scarcely ever used, as newer apparatus, much more convenient and more sensitive, has been invented. Page 63.

8. If we give the lower plate of the condenser, which is connected with the electrometer, a positive charge L, then, when we put on the upper plate and connect it to earth, a certain fraction (x) of the charge will be bound on the lower plate. Therefore the quantity of bound electricity below $L_1 = x \times L$. If now we touch the lower plate, then this has, in a certain measure, a new charge $L_1 = x \times L$. When touching the upper plate for the second time, the same Pages 73, 75.

fraction of the present charge will also be bound again on the lower plate, therefore $L_2 = x \times L = x^2 L$.

If we continue the touching, first above, and then below, we get:

On the lower plate (+E)	On the upper plate (−E)
Original charge $= L$ . . . . Bound: $L_1 = x.L$	. . . . 1. Touch (above) . . . .
1. Touch (below) Residual charge: $L = x \times L$ (as above) . . . . Bound: $L_2 = x \times L_1 = x^2 L$	. . . . 2. Touch (above) . . . .
2. Touch (below) Residual charge $L_2 = x^2 L$ . . . . Bound: $L_3 = x \times L_2 = x^3 L$	. . . . 3. Touch (above) . . . .
. . . . Bound: and after the n^{th} touch below as residual charge: $L_n = x^n \times L$	. . . . n^{th} Touch (above) . . . .

These values L and L_n we can measure strictly by the electrometer, and hence calculate,

From the equation $x^n L = L_n$ follows: $x^n = \frac{L_n}{L}$; therefore

$$x = \sqrt[n]{\frac{L_n}{L}} = \text{num}\left(\frac{\log L_n - \log L}{n}\right); \quad K = \frac{1}{1-x}.$$

With careful measurement by our standard condenser—the atmosphere being dry, with not more than 48 per cent. moisture—the original charge appears as $L = 5{\cdot}0$ scale units. After ten double touchings the electrometer indicated $L_n = 4{\cdot}7$; therefore

$$x = \sqrt[10]{\frac{4{\cdot}7}{5{\cdot}0}} = \text{num}\left(\frac{\log 4{\cdot}7 - \log 5{\cdot}0}{10}\right) = 0{\cdot}9949.$$

Accordingly $1 - x = 0{\cdot}0051$; therefore the required *dielectric strength* of the condenser is

$$K = \frac{1}{0{\cdot}0051} = 196.$$

Another measure, when the air contained nearly 45 per cent. moisture, yielded $K = \cdot 205$; therefore, as the dielectric strength, we may take

$$K = 200.$$

This method of determining the dielectric strength is indeed not scientifically accurate, but for our purposes quite accurate enough, and also easy and quick to accomplish (Appendix, 22, p. 397).

In case the plates of the condensers do not insulate well, which is indicated by the falling of the leaves after putting on, conducting to earth, or taking off the upper plate, then the polished surfaces must be put under a stream of water, wiped with a soft cloth and dried (holding them by the insulated handle) over a spirit lamp, turning them obliquely until the humidity quite disappears. Before using the plates again they must be allowed to cool.

9. This method of graduating the electrometer by means of two condensers is minutely described in *Zeitschrift für d. phys. und chem. Unter.* (Berlin, Julius Springer), iv. p. 293. Page 76.

10. The effect of an electric jar depends, in addition to the extent of the coatings, mainly on the power of insulation possessed by the glass. Jars which have to bear a high electrical tension, and give strong sparks, must be of thick glass and free from flaws. After the tinfoil has been pasted on, the glass must be very carefully cleaned and dried, and, whilst still warm, brushed over (on the uncovered parts) with shellac-varnish, otherwise all one's trouble will be useless. To test whether the glass possesses its full power of insulation, the simplest method is, after having well cleaned and dried it, to rub it with well used amalgamated leather—the more it crackles and yields sparks, the better it will insulate. Page 80.

11. Töpler (of Riga) and Holtz (of Berlin) discovered influence machines simultaneously in 1864. Many modifications of these are now in use. In many cases the glass discs are replaced by ebonite ones, and the number of discs increased, or contrivances are added to cause the machine (by friction with metal brushes on insulated buttons on Pages 102–111.

the rotating disc) to be self-exciting (Wimshurst, Holtz). More important are the machines with several (up to 30) rotating discs, which have almost the same effect as if several machines were connected together, so that one machine electrifies the armature of the next. These last machines, with free conductors, then yield sparks of very great power (high-tension machines, as they are called), or the machines are "coupled" together, *i.e.*, the electricity of the like poles is accumulated in common conductors. In this way larger quantities of electricity of the same degree of electrification are yielded, as if by a single machine. We shall meet with similar combinations of electrical apparatus in galvanic electricity.

Page 122. 12. Let us suspend the ball K (fig. 60, p. 124) by silk threads and connect it with the electrical machine placed at some distance away, the other pole of the electrical machine being connected to the earth. The aluminium electrometer, with candle attached as shown in *l*, fig. 60, is used and the case of the electrometer is connected with the earth wire.

The ball has a radius $r=5$ cm. We place the candle exactly 500 cm. from the centre of ball and put the machine in motion: the divergence p is 3·1 divisions of scale, or $200 \times 3{\cdot}1 = 620$ volts (*cf.* p. 159). Therefore

$$V = p \times \frac{e}{r} = 620 \times \frac{500}{5} = 62{,}000 \text{ volts.}$$

Since the pole connected to earth has the zero degree of electrification, the difference of the poles of the influence machine is $62{,}000 - 0$ or 62,000 volts. These measurements can only be verified in a large clear space.

Since the degree of electrification of equipotential surfaces decreases with their distance from the electrified body, a rather long insulated conductor, one end of which we bring near to the electrified body, will dip into different levels. Then from the higher level there will flow into the conductor as much electricity to the end furthest away as is necessary to make up the balance of the difference of level. Let us, for example (fig. 24, p. 46), imagine the electroscope connected

by a wire in the positive electric field of the ball (C), then a certain quantity of +E leaves the neighbouring electroscope B for A; in B there is now less, and in A more electricity than before. This difference remains, if, first the connecting wire, and then the influencing body C is removed. Now A has more electricity than its surroundings and must indicate +E (p. 50). In B it is the opposite. Hence we see why, in this case, in A as in B, only positive electricity can be conducted away. From this point of view the influence experiment (p. 46) appears to us in a new light. To go into this matter would be beyond our domain; we therefore refer the reader to Müller-Pouillet's *Lehrb. d. Phys. und Meteorol.*, ninth ed., 1890, vol. iii. pp. 141–144.

13. In order that the electric lines of force may appear in all their beauty, the sulphate of quinine must be added to the oil of turpentine only just before the experiment. Instead of quinine, dry sawdust or coal-dust is sometimes recommended. The mixture is useless next day. If the flat glass vessel (A, fig. 62, p. 125) is illuminated from below (by means of a mirror bent at an angle of 45°), the experiment may be made viewed objectively by fixing over the glass vessel a large total reflecting (right-angled) glass prism and then projecting the horizontal rays in the usual way. This experiment is not easy to carry out. (It was described first in an English scientific journal in 1891.) Page 125.

14. On the Egyptian temples in Edfu and Dendera there are inscriptions which have been deciphered by Dümichen and Brugsch. They state that the high poles covered with copper plates and with gilded tops were erected "to break the stones coming from on high" (J. Dümichen, *Baugeschichte des Dendera-Tempels*, Strassburg, 1877). Page 131.

Benjamin Franklin, in a paper read before the Royal Society of London 1747–1748, stated how, by means of a paper kite, "lightning could be drawn from the clouds," but he was laughed to scorn. He himself performed the experiment in 1752, after many others had made the attempt. Professor Richmann repeated the attempt in St Petersburg in 1753, but was killed by lightning in so doing. Prokop Divisch learnt of this through the newspaper, and in a pamphlet to

the Berlin Academy described an apparatus by which the lightning could be conducted to earth without damage. Accordingly, in 1754, he erected his first conductor, whilst Franklin's was first erected in 1760 in Philadelphia. Thus—if one excepts the ancient Egyptians—Divisch erected the first lightning conductor.

Page 149. 15. If we make the threads of the pendulum long enough and the angle of divergence so small that we can consider the distance of both plates (B, fig. 72, p. 148) $pq = d$, without any great error, as the small side of a right-angled triangle (oqp), it follows, according to a simple geometrical rule, that $k : g :: d : l$, therefore $k = \frac{d \times g}{l}$, where k, in fig. 72, represents the component of gravity acting on the pendulum p. If the pendulum p has the mass $= m$, then the gravitation pull acting downwards is $g = m \times g$, and that of the component of gravity $(k) = m \times k = m \times d \times \frac{g}{l}$. This component now keeps the forces of repulsion of discs p and q electrified with equal quantities of like electricity, in equilibrium. Now, as we saw (p. 62), the force of electric repulsion between two bodies similarly electrified (at a distance d) is

$$a = \frac{e \times e''}{d^2} = \frac{e^2}{d^2}.$$

Therefore it is $m \times d \times \frac{g}{l} = \frac{e^2}{d^2}$. Now let $d = 1$ cm. and $e = 1$ (electrostatic unit of electrical quantity). Then the formula above will be simply $m \times \frac{g}{l} = 1$, or $m = \frac{l}{g}$. Then, if the pendulum is pushed 1 cm. to the side by the electric force of repulsion, the force of repulsion will equal exactly 1 *dyne*. For the pendulum, whose mass $m = 1$ (gramme), $\frac{l}{g} = 1$, therefore $l = g = 981$ cm. is necessary. If, on the contrary, as in our case, the length of string is confined to $l = \frac{981}{4}$ cm., then, since $m = \frac{l}{g}$, $m = \frac{981 \div 4}{981} = \frac{1}{4}$, therefore $m = 0{\cdot}25$ gramme.

16. In our comparison between electricity and gravity, we have partly followed the methods of Balfour Stewart and Haldane Gee, as given in their *Practical Physics.* The part of this work which treats of electricity offers a number of excellent exercises and experiments, which may be quite as well performed with the apparatus used by us. The methods are a little too concise for beginners, otherwise the study of this book is much to be recommended. Page 155.

17. Electric potential is usually defined as follows: "*The electric potential of a body is the work which must be performed to bring the body from an unlimited distance*, and therefore from the absolute electric zero level *to an amount of (positive) electricity equal to* 1." Since in the practical performance of experiments we always take the electric level or potential of the earth as 0, we have formulated the meaning of electric potential in a correspondingly simpler way. No error can be made, since we have always to do with potential *difference.* The choice of the zero level is immaterial. Page 157.

18. The electrometer. Page 31.

I. The electrometer should always be to the electroscope what the thermometer is to the thermoscope, *i.e.*, the statements with regard to the single portions of the apparatus must not only admit of comparison, but also of calculation. In the thermometer the two "fixed points" (freezing and boiling point) denote a particular value. The electrometers must either be graduated (by the addition of equal quantities of electricity), or they must be so constructed that the divergences are in proper proportion to the charge, and afford a means of calculation. Our electrometer fulfils both these conditions with an accuracy sufficient for our purpose. If with 1 charge the divergence $= a^{\circ}_{1}$, then the divergence with a charge n times as great $= a^{\circ}_{n}$, and indeed the following ratio is found: $\tan a^{\circ}_{n} = n(\tan a^{\circ}_{1} + a) - b$, where a and b are constants, which in good electrometers of this kind have so small a value that for school purposes we can state: $\tan a^{\circ}_{n} = n \tan a^{\circ}_{1}$. Our electrometer is, therefore, almost a tangent electrometer.

Mechanical instrument makers often sell under the name "electrometer" an electroscope with 1 or 2 leaves, fitted with

a simple graduation scale. These do not deserve the name electrometer.

II. The electrometer (fig. 15) is made with the graduated scale. This scale (fig. 13) is movable and only used for the demonstration of graduation by projection, or for practical experiments in class. For self-graduation a graduated scale is mounted on a plane mirror which forms the back (g_1, g_2, fig. 15, are the handles). The metal case is 130 mm. high, 140 mm. broad, and 95 mm. deep (so that the leaves may not touch).

For many experiments, a paper leaf is better, on account of its durability. For this purpose we use an extra ebonite stopper with amber tube, conducting rod, and a paper leaf. Great care must be taken when taking out the aluminium leaf. The best way is to place the ebonite stopper in a glass tube into which it fits, and which stands on a wooden base. If the hook (*e*), fig. 15, at the end of the wire spring is put on the conducting rod, then the aluminium leaf is protected from all accidental charges. This "electrical insurance" may also be used for the explanation of the action of Meldes' lightning conductor.

III. For quantitative experiments it is advisable to place a C-shaped piece of wire gauze before the front and behind the back plate, fastening the loops (*bent at right angles to the net*) to the little knobs (*c*, fig. 15). These may be obtained with the instruments.

Very worthy of recommendation is a contrivance of Professor K. Noack (*Philos. d. Naturw.*, vol. ii., "Elementary Measurements in Electrostatics") to make glass plates conduct well, namely, by putting them for a short time in Böllcher's silvering solution (or phosphoric acid).

A conductor, which could be moved aside, was fitted to the earlier electrometers to increase the sensitiveness of the instrument—for some experiments,—and to be able to use the apparatus also as a discharging electrometer. But as the delicate aluminium leaves were easily injured by it, and as the capacity-measurer (fig. 42) furnishes a convenient discharging electrometer, this secondary conductor is entirely omitted.

IV. If the aluminium leaf should get bent—during trans-

port of the instrument or when putting on the stopper (as in A, fig. 157)—the front glass plate must be taken out, and you must insert a pair of flat, polished pincers with rounded ends, so that the bent part of the aluminium leaf (without being touched) may come just within the points (B, fig. 157); turn these, in the manner shown by the arrow (1), until the bend in the leaf is the reverse of what it was before, then carefully draw the pincers downwards along the leaf (as shown by arrow

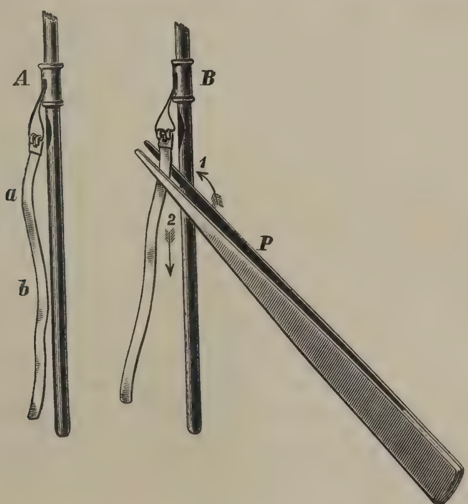


FIG. 157.

(2)). Do this several times until the leaf has become quite straight. This operation must often be repeated after several days.

19. *How to put in a new aluminium leaf in the electrometer.* Page 31. We must first examine whether the sheet of aluminium is of the proper size. A piece of millimetre tracing paper of 105×210 mm. is folded together at the middle of the long side. About 5 mm. of the edges of one of the halves so obtained are cut, the aluminium leaf is laid between, and the edges overlapping it are turned over and gummed fast. The whole is then placed on a piece of smooth cardboard, a ruler is laid on it, and with a sharp knife (with one draw of the blade if possible) strips of the breadth of the conducting

rod are cut (*i.e.*, for the electroscope and the earlier electrometer 3–3·5 mm., and for the new electrometer 2 mm. broad).

If the paper hinge is still good, the piece of the old leaf is first removed with a pair of pincers and the lower edge of the paper hinge is gummed (on the outer side). Then take hold of the new aluminium leaf with the flat pincers (P, fig. 157) near the upper end, and put the leaf carefully to the paper hinge (the conducting rod must be held vertical, or, better, clamped in a support). When the leaf is quite parallel to the rod (not a breath!) the upper end of the aluminium leaf must be pressed to the gummed place. After smoothing the leaf as on p. 395, if necessary, it is cut to the same length as the conducting rod.

The hinge is made of red tissue paper (carmine because it conducts the best)—breadth the same as the leaf, length about 5–6 cm.[1] From one end about 1 cm. is carefully folded over, and a small piece is cut out of the middle of the folded part, then a needle is pushed through, and so pressed with the thumb that two round loops are formed. The upper piece of tissue paper is now cut so that a piece of about 2 mm. long is left below the loops. This is put over the wire loop, so that the paper loops just fit on the wire. Now the lower end of the shorter paper strip is gummed and pressed on the other slip of paper with the pincers. After the hinge so formed is quite dry, the longer strip is cut to the same size as the other and the aluminium leaf is put on.

Page 159. 20. The force of repulsion which an electrified and insulated ball exercises on a similarly electrified point varies, according as the point is very near the surface (without touching it, however), or on the surface itself and inside the ball. Let d be the electric density of the ball, then the force of repulsion (a):

(1) On a point outside, but very near the surface of the ball (*e.g.*, on a very small pendulum, immediately after touching with the ball), $a_1 = 4\pi\delta$.
(2) On a point on the surface of the ball $a_2 = 2\pi\delta$.
(3) On a point inside the ball $a_3 = 0$.
(4) On a point on the unit of surface (1 sq. cm.) $a_4 = 2\pi\delta^2$.

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[1] Lately Professor K. Noack has recommended (as being more suitable for the aluminium leaf) a loop made out of the bark of a dried reed.

Now this force of repulsion is by some authors called *tension*, whilst other physicists by *tension* understand the measure of work of the degree of electrification (potential). On account of the confusion in the name *tension*, in reading works on electricity, care must always be taken in finding out in what sense the word is used.

21. Soapstone (steatite) is a rather dense talc of fibrous nature, easy to use, but becoming hard after heating. Of all bodies hitherto observed, it is the only one which always becomes negatively electrified after friction, *i.e.*, it is quite at the end of the electrostatic series. Dr P. Meutzner, rector of Annaberg, first drew attention to this (*Zeitschr. f. phys. und chem. Unt.*, ii., 1889, p. 342). Before being heated the conductivity of steatite is remarkable. Pages 13, 16.

22. As unit of capacity we have that of a body which requires 1 coulomb for a charge of 1 volt. This unit of capacity is called 1 *Farad*. For practical purposes it is too great, therefore the millionth part or 1 microfarad is used as practical unit of capacity. Page 159.

An air condenser has a capacity of 1 microfarad if the stratum of air is 1 mm. and the diameter of the plate = 6 m.

In order to have a capacity of 1 microfarad, an insulated ball would have to have a radius of 9 kilometres.

The capacity of the sphere of the earth ($r = 6372$ km.) is 708 microfarads.

Condensing plates (with mica as insulator) are used to determine the capacity of condensers; these possess a certain fraction of a microfarad. The multiplying power of the condenser determined by us only gives the ratio of the capacities (p. 72).

23. By the employment of very strong electro-magnets, Faraday in 1845 proved that all bodies exhibit magnetic properties, but not in the same way. While, for example, iron, nickel, cobalt, etc., are *attracted* by both poles of the magnet, with other bodies, such as antimony, bismuth, zinc, it is just the reverse—that is, they are repelled by both magnetic poles. The first group, of which *iron* is the representative, Faraday called *paramagnetic*, the others *diamagnetic*. The line joining the two poles of a magnet is Page 169.

called the magnetic axis, and a line drawn across the middle of the plane perpendicular to the axis is called the *equator*. If a paramagnetic rod is suspended between the pole-pieces of a strong electro-magnet, it takes up a position parallel to the magnetic axis, or axially—that is, parallel to the magnetic lines of force. A diamagnetic bar, on the

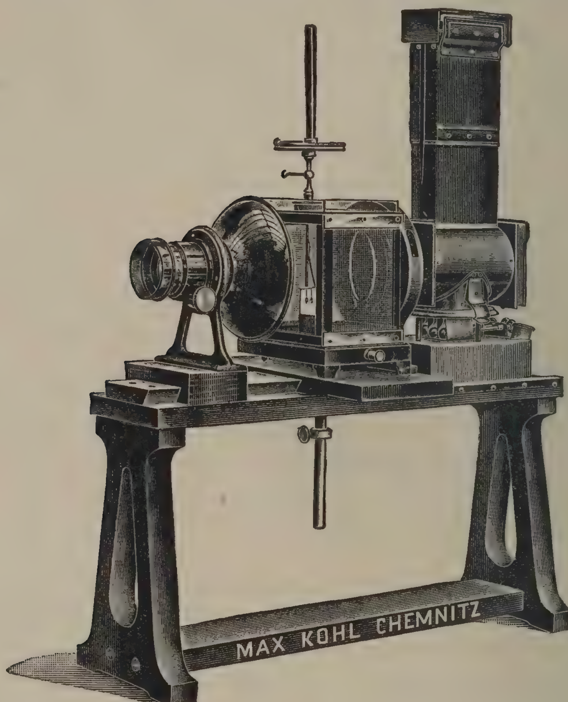

FIG. 158.—Steady projection table.

other hand, places itself equatorially—that is, perpendicular to the lines of force. Weber explained this by the hypothesis that molecular currents of unlike direction are induced in the diamagnetic bodies by the action of the magnets. A similar action takes place in dielectric bodies; in fact glass and other non-conductors are strongly diamagnetic.

Page 198. 24. The projection table (fig. 158), apart from the question of cost, has another advantage over the projection lantern,

namely, that the apparatus to be projected stands quite clear and exposed to observation, so that the manipulation of the experimenter can easily be followed. The lamp-stand and the condenser may be raised either separately or together (p. 387). The plate on which the apparatus is set up has an adjustable extra plate and an opening of 50 mm. diameter, so that even taller objects, such as thermometers and burettes, can be placed on it and their images projected. This is especially useful with the new prismatic burettes of fused plate glass, divided into c.cm. As illuminant small electric lamps may be used, or the three-wick'd petroleum lamp, as given in the illustration. I myself have used electric incandescent lamps of 50 candle power and 120 volts, silvered on one side (p. 387), though a threefold Nernst lamp of 240 candle power has also given very good results, as has a very small hand-regulated arc lamp of 200 candle power with current regulator. Of course the lamp must be in a suitable case. Where there is plenty of room, the steady projection table (fig. 158) may be very advantageously used. The double slide allows the insertion of bodies longer than the lantern.

25. The so-called "fundamental experiment" of Volta is Page 201.
meant to prove that two plates of different metals, which by means of two insulated handles are brought into contact and again withdrawn from each other in a parallel direction, exhibit a difference of electric potential, which depends on the *nature* of the metal used and *not* upon the magnitude of the surfaces. The cause of this electrification "by contact" of the different metal plates Volta called "electromotive force," which formed his contact theory. When one zinc and one copper plate is used, the zinc shows positive electricity and the copper negative, which signs are reversed at the protruding ends when the plates are immersed in unacidulated water, but remain the same for the parts of the metals within the water. Metals and carbon may be arranged in a series, so that each metal, when in contact with the following one, is charged electro-positively, thus corresponding to the electrostatic series in frictional electricity.

VOLTAIC SERIES.

+	Zinc	Lead	Tin	Iron	Copper	Silver	Gold	Carbon	Graphite	Manganese ore

In this case Volta's law holds good: the electromotive force between any two members of the series is equal to the sum of the electromotive forces of the intermediate combinations. For example:

$$\frac{\text{zinc}}{\text{copper}}=\frac{\text{zinc}}{\text{tin}}+\frac{\text{tin}}{\text{iron}}+\frac{\text{iron}}{\text{copper}}$$

and

$$\frac{\text{zinc}}{\text{carbon}}+\frac{\text{carbon}}{\text{copper}}=\frac{\text{zinc}}{\text{copper}}, \text{ etc.}$$

Since fluid conductors are not subject to the series law, Volta named metals and carbon "electromotors of the first class," and the fluid conductors "electromotors of the second class." This division is further justified by the fact that metals only are heated by the electric current, while, in the case of electromotors of the second class, a chemical decomposition, which we have considered as the cause of electromotive force (see p. 200), takes place. Fluids which are not decomposed by the electric current, vaseline oil, alcohol, and even chemically pure water, *do not conduct the current.*

Page 203. 26. In the case of the Bunsen cell, a solution of bichromate of potash is usually employed, which, on account of the setting free of chrome alum [$KCr(SO_4)_2$, $12H_2O$], is very damaging. Much better is bichromate of soda, with which scarcely any chrome alum is set free. The following mixture, which it will be better to obtain from a chemist, has given good results:—100 parts by weight of water, 25 parts of crude sulphuric acid, 12 parts of bichromate of soda. To the solution thus prepared may be added a little sulphuric mercury or mercuric oxide, in the proportion of 3–4 grammes to 1 litre of fluid, by which the zinc plates will be kept amalgamated and bright. In another chromic acid solution much in use, 50 grammes of crystallized chromic acid are dissolved in 1 litre of water, and then 5 c.cm. sulphuric acid are slowly added, with mercuric oxide as above.

27. *Lametta* threads are those threads of beaten metal used for decorating Christmas trees. The wavy kind is preferable. In the experiment (fig. 109) two or three rolled loosely together may be used. Failing this, a small strip of exceedingly thin tinfoil may be used, 2–3 mm. broad and 50 cm. long. Page 234.

28. *I.* The simple Ampère's table or parallelogram here used (fig. 98) requires a rather stronger current than the ordinary one employed, in which the solenoid rests on steel terminals in mercury cups, but the mercury must be very pure and the solenoid well balanced. This is done by altering the position of the mercury cup or by turning outwards the end of the rod carrying the silk thread. The silver points recommended by some instrument makers do not give at all good results. Page 220.

To give a solenoid with a single winding (R, fig. 98) an east-west direction, a current of 6–8 ampères at 4 volts is required. The wire frame of ten turns takes its position with a current from a fresh immersion cell of 5–6 ampères at 2 volts. When needful, the action of the earth's magnetism may be strengthened by inserting beneath the base (exactly under the mercury cup) a bar magnet, with its south-seeking pole turned to the north.

II. This Ampère's table may also be used as the model of a tangent galvanometer, if a short magnetic needle (for example, B, fig. 110) is used, the length of which, from one bend to the other, is 20 mm. Then a copper wire ring (fastened in a groove), 3·5 mm. thick, diameter = 20–25 cm., is enough. If the ring is placed at a distance = $\frac{1}{4}$ of its diameter (from the middle of the needle), then the tangents of the angle of deflection (*cf.* p. 312) are directly proportional to the strength of current independently of the length of the needle. This kind of tangent galvanometer was first proposed by Helmholtz and Gaugain. Page 236.

29. In the work: *Essai théorique et expérimentale sur le galvanisme*, par Jean Aldini, Paris, An. xii., MDCCCIV. (1804) [with the dedication: "À Bonaparte, citoyen, premier consul et président"], the following remark occurs: "M. Romanosi, physicien de Trente, qui a reconnu, que le galvanisme faisait décliner l'aiguille aimantée." (I am indebted for this notice to Professor Dr O. Chwolson, of St Petersburg.) Page 230

Page 246. 30. In Fleeming's standard cell, which may also replace the small cell shown in fig. 92, the zinc plate dips into a solution of 55·5 parts of zinc sulphate in 44·5 parts of water (specific gravity = 1·2 at 20° C.), and the copper plate into a solution of 16·5 parts of copper sulphate in 83·5 parts water (specific gravity = 1·1 at 20° C.). The zinc rod must be well amalgamated if it is not chemically pure. The glass vessel (fig. 113) may consist of one piece. But as ground glass stop-cocks are dear, the apparatus may be constructed of single parts, joined by rubber tubing, with ebonite stop-cocks or pinch-cocks. Only constant cells can be employed for any experiments in measurement. In order that they may work as uniformly as possible during use, after setting up, they should work for about ten minutes in short circuit, *i.e.* with the pole terminals connected by a short thick copper wire, so that a (certain) condition of equilibrium may be established in the interior of the cell.

Page 248. 31. *I.* In our experiment (fig. 114) the galvanometer needle is under the influence of two directing forces: that of the earth and that of the bar magnet. The first strives to impart to the magnetic needle a north-and-south, the latter an east-and-west direction; therefore it takes a middle direction (the resultant). The nearer the two magnets are pushed to the compass, the more its directing force overpowers that of the earth's magnetism, that is to say, the angle which the galvanometer needle makes with the magnetic meridian grows continually greater. Since the bar magnets are strongly magnetized and fairly long (40 cm.), the middle part of their magnetic field, which is occupied by the galvanometer needle, is homogeneous, *i.e.* the intensity is almost constant and the lines of force are parallel. Upon this depends, when the needle is not too long, the correctness of the method of graduation used by us (*cf. infra, III.*).

When graduating the galvanoscope, that intensity of current which gave a deflection $a_1 = 14°$ was taken as the arbitrary unit of intensity of current. It is recommended, for completing the graduation scale, to represent the results of the graduation *graphically*, by transferring to paper ruled in square millimetres as horizontal abscissæ at a distance

of 1 cm. the current intensities 0, 1, 2, 3 . . ., and as ordinates (vertical) the *number* of degrees in arc, which must be read off accurately to a tenth, when the points obtained may be joined into a curve. This curve, when the measurements are more exact, may be used as a means for the reduction of the scale of degrees to the graduated scale, and for inserting the fractions of the scale of degrees not observed (halves or tenths). Its course also furnishes a good criterion of the correctness of the measurement.

II. Professor E. Grimsehl has invented a tangent galvanometer, with movable parts, very suitable for practical school graduation work (described in the *Unterrichtsblättern für Math. u Naturw.*, vii. 1902, No. 5, pp. 104 *sqq.*, and in the *Phys. Zeitscht.*, III. (1902), No. 20, pp. 462 *sqq.*).

The author has kindly permitted me to repeat the description of this instrument and the method of graduation used.

The board (18×24 cm.) on which it stands (see next page) has in its centre a rod of brass 12 cm. in height, at the top of which is a compass with short needle set on a base consisting of a mirror, while at right angles to the needle are the aluminium indicators. The indicators revolve on a scale divided into degrees. The base-board G is provided with two narrow side rails which serve as guides to the sledge of the circular conductor [R_1]. In the middle of the stand of R_2 is a groove, so that the conductors may be placed in any prescribed position. One of the circular conductors (R_1) is single, the other (R_2) double. Both have a radius of 10 cm. The binding screws of both are so placed that on the simultaneous connection of the two conductors the binding screws are on the same side.

III. Graduation of the tangent galvanometer of E. Grimsehl by the method of multiplication. Page 250.

"Fig. 159 shows the arrangement in diagram. The two poles of a constant source of electricity E, such as a single accumulator, are connected on the one side with one of the binding screws of a commutator, on the other side with the rheostat R. The other binding screw of the rheostat is connected with the second terminal of the commutator.

Between the two earthed terminals k_1 and k_2 of the commutator, the connecting screw k_3 is inserted. Now k_1 and k_3 are connected by means of a double conducting wire (2 m. long), S_1 with the terminals of the single circular conductor L_1, and k_2 and k_3 by another double conducting wire S_2 with the terminals of the double circular conductor L_1. By this arrangement a controllable current flows from the accumulator E and through the rheostat R through the conductors L_1 and L_2 in succession. The currents flowing through L_1 and L_2 may, therefore, be said to be exactly

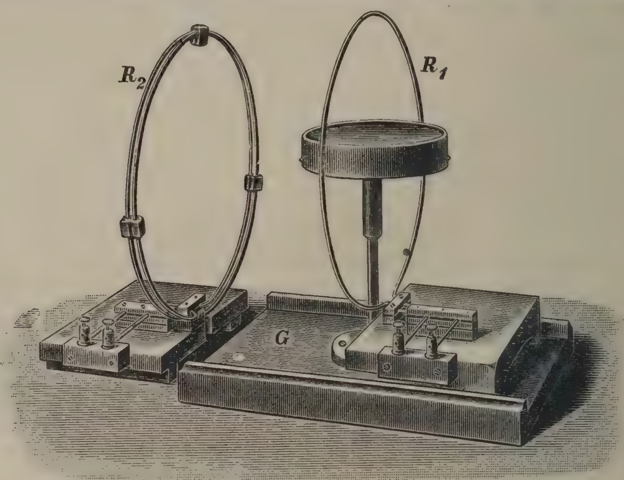

FIG. 159.—Grimsehl's movable tangent galvanometer, $\frac{1}{5}$ natural size.

equal. If now L_1, when traversed by the current, produces a certain magnetic action, then the conductor, when brought to this point, causes an action attributable to a double intensity of current; if both conductors L_1 and L_2 are placed at the same spot in the space, then the united action of the two conductors answers to the threefold intensity of current.

"After the compass B has been set in the magnetic meridian, the single conductor must be placed round the compass, and you must close the circuit and put in it as much resistance as will cause a deflection of 6°. The same current traverses the double conductor at a distance of 3–4 metres (at the side), so that it exerts no influence upon the magnetic

needle. Now the conductor L is removed and L_2 put in its place, without, however, changing the position of R. Now a deviation of 11·5° follows, due to the double current action. Lastly, without changing in any way the current intensity, L_1 and L_2 are simultaneously placed round the compass. The threefold current intensity produces a deflection of 17°. Placed in tabular form, we have:

Strength of Current.	Deflection.
1	6°
2	11·5°
3	17°

To check and to compare and correct errors the same

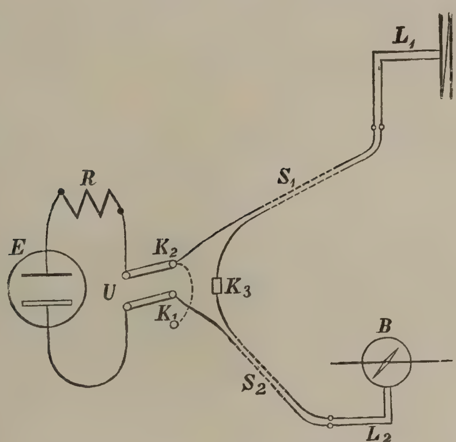

FIG. 160.—Diagram of graduation process.

experiments may be repeated, but with the reversed direction of current.

"Now let us perform another series of experiments. The single conductor is again placed round the compass and the double one removed. R is regulated so that the conductor L_1 produces a deflection of 11·5°. Now take it away and replace the double one (L_2) with the same intensity of current; the deflection = 22°, and again both in position give 31°. Evidently, in the second series, the current intensity must have been twice as great as before, hence the deflections 11·5°, 22°, 31°, correspond to intensities of 2, 4, 6. These

results must be added to the table of those obtained before. A third series is begun by getting a deflection of 17° with the single conductor L_1; throughout the whole circular conductor, therefore, there is an intensity 3, as obtained from the first series of experiments. The deviations given by L_1 alone, L_2 alone, and $L_1 + L_2$ are observed. The results are 17°, 31°, 42°, which imply current intensities of 3, 6, 9. A fourth series begins with a deviation of 22°, single conductor, and following the same calculation as before, we get 22°, 38·5°, 48·2, and the corresponding intensities, 4, 8, 12.

"Proceeding thus, we get all the current intensities, which will be expressed by multiples of 1, 2, 3.

"The following table contains, according to these calculations, current intensities from 1–64, with their corresponding deflections.

Current intensities—																
1	2	3	4	6	8	9	12	16	18	24	27	32	36	48	54	64
Deflections—																
6°	11·5°	17°	22°	31°	38·2°	42°	50°	58°	61°	67·5°	69·5°	73°	74·5°	78°	79·5°	81°

"The results of these observations are used for the construction of a curve, in which the deviations are the abscissa and the corresponding strengths of current are the ordinates. The values observed give points sufficiently near to determine the curves with the greatest accuracy.

"It is worthy of remark how exactly the curves drawn in this empirical manner coincide with the calculated tangent curve. The choice of the first angle of 6° is founded on the fact that $\tan 6° = 0{\cdot}1$ (nearly):—but of course any other first value may be taken.

"The curve drawn may be used to read directly the intensity of an unknown current which exhibits a known angle of deflection. If it is required to express the current intensities in ampères (for example), instead of on the arbitrarily chosen scale, it is only necessary to obtain the factor of reduction by comparison with known intensities, if it is not desired to find it by means of the formula $\frac{5r\mathrm{H}}{\pi}$. In the present case the reduction factor for $\mathrm{H} = 0{\cdot}2$, $r = 10$ cm., and $\mathrm{R} = 3{\cdot}18$."

This elegant method of graduation has the advantage over the other one used by us (p. 248) that the magnetic field generated by the earth magnetism remains unchanged, while, in the other case, the moving of the magnet causes a change in the intensity of the field.

Comparative experiments have proved that, with sufficient care, a galvanometer for class use may be graduated by means of bar magnets; but Grimsehl's method is more accurate, though not adaptable to every compass.

32. The six-fold manometer (fig. 127) is a modification of Looser's eight-fold instrument, which was specially constructed for the demonstration of heat conduction in metal rods (see Looser's *Experiments in Heat, etc., by the Use of the Double Thermoscope.* Rob. Müller, Essen-Ruhr). Page 283.

The instrument (fig. 127) can be employed for various experiments, and in this case, for example, is suitable for comparing the resistances of metal wires. The resistances of wires of the same material and equal length, but of different sectional area, or of the same sectional area, but of unequal lengths, may be compared in a very clear manner. By its means also Joule's law may be proved [see *Guide to Thirty of the most Important School Experiments with Differential and Double Thermoscope and the six-fold Manometer.* Max Kohl (Chemnitz) and Ferdinand Ernecke (Berlin) 1903].

33. The solenoid galvanometer (figs. 130 and 131). Only during the last ten years has this instrument been put into the list of ordinary school apparatus, and now it has quite superseded the magnetic needle galvanometer. The fixed cylinder of soft iron (*e*, fig. 131) inside the solenoid coil concentrates the magnetic lines of force (p. 366), and so the deflecting action of the magnet on the solenoid traversed by the current is much strengthened. Page 289.

The construction described here is taken from one of the four or five types which have come under my notice, and which I consider best for school purposes, as the plug is only required when the apparatus is used as ampèremeter; otherwise turning the handle is sufficient. The firm of Keiser and Schmidt (of Berlin) have fitted their new machines with a contrivance by which the cover can be

taken off and set on again instantaneously. The apparatus has a double-jointed indicator, so that the red arrow (with white index) is in the plane of the scale, by which means when it (the apparatus) is placed sideways parallax is avoided. In class experiments this is very important and in other apparatus of this kind can scarcely be attained. The apparatus is rather delicate, and care must be taken when putting on the glass case not to knock the axis or the solenoid spring.

A little *stronger* (because they have a continuous axis), and at least as sensitive, are the solenoids with peg-commutator, as made by other firms; but, as a rule, in most of these the indicator is fitted in front of an opaque scale, and hence is only visible from the front, or there is another indicator behind.

In all these galvanometers, any range of measurement (*vide* p. 292) may be affixed, according to needs. Many firms also supply solenoid galvanometers having a very small coil resistance for thermo-electric currents, *i.e.* for measuring resistance according to the zero method (p. 295). These instruments have no shunt and are only fitted with extra sliding resistances for use as voltmeters.

Page 300. 34. The electric incandescent lamp was invented (1855) by Henry Göbel, a Hanoverian, who emigrated to New York. Göbel was engaged by the company founded to work Edison's inventions (1881), and since that time the so-called Edison's incandescent lamp has appeared on the market. That now universally used is provided with a screw socket,[1] which can be quickly put on and taken off, and affords a very effective contact.

Page 301. 35. The oxyhydrogen and hydrogen voltameters (fig. 134) have this advantage over those usually used, namely, that—on account of the proximity of the electrodes—the resistance is very small or about ten or twelve times less than in the original apparatus of Hoffmann; hence more gas is set free in the same time. Also, by removing the rubber stopper, the in terior of the glass tubes can be easily cleaned. The glass balls at the top entirely prevent the acid from spurting out. By

[1] In England, one with a bayonet catch.—*Ed.*

connecting a rubber tube to the small pipes in the balls, the gases may be intercepted as they are generated.

The firm of Max Kohl (of Chemnitz) in their latest apparatus have narrowed the lower part of the tubes, so that they can be more firmly fixed to the stand. Although by this contrivance the pressure of gravity on the rubber stopper has been much lessened, it is advisable to support it underneath by means of a piece of metal of the form given (SP, fig. 134).

To empty the apparatus it is only necessary to remove the funnel from the ring, and then let the liquid run out into a vessel held underneath while the cocks are opened. It is better to rinse the tubes with water three or four times after use, and when *not* in use the rubber stoppers should be taken out, and wrapped up in waxed paper, or at least put in very loosely, as in time the rubber sticks to the glass.

Should the tubes become very dirty, they can be cleaned by using a long thin rod of wood or whalebone, one end of which is wrapped round with soft linen. This should be steeped in spirit and carefully pushed up and down the tubes. If this is not sufficient, nitric acid should be used, followed by water.

36. If, in our demonstration galvanometer (*cf.* fig. 112), a Page 311.
constant current of sufficient strength is led through the ring when it is in a vertical position so as to produce a divergence of more than 45°, then, by lowering the ring, a divergence of 45° may always be attained. In these conditions the apparatus is most sensitive. With ordinary compasses the angle can only be read up to $\frac{1}{5}$ degree; in others, with a large circle, up to $\frac{1}{10}$.

For smaller angles, this makes an appreciable fraction of the angle of deflection; whereby (taking 25° as equivalent to 5°) the falling off in the intensity of the current may amount to 1°, which corresponds to 4°.

On the other hand, with greater angles—such as those above 60°—the tangents change very quickly (that is, the degrees on the scale become much smaller), for which reason the errors in reading again have a great influence on the result. Hence a divergence of 45° is always aimed at, as

in this case the influence of the error is the least troublesome. Our galvanometer rotates on its stand, hence, when a certain deflection is occasioned by a current, the compass can be turned according to the needle, until *it is again on the zero point.* In this case the current intensity is proportional to the sine of the torsion angle (δ) of the compass ($J = \kappa' \sin \delta$, where κ' is a constant factor). For a measurement such as this the instrument is first set, so that the indicator of the magnet needle at rest and the fixed sight (V, fig. 37) are exactly at 0. As the fixed sight does not turn with the compass, the degree on the graduation scale of the torsion angle may be read. This galvanometer is, therefore, also a sine galvanometer. The manipulation of it, on account of the turning, takes up more time than in the case of the tangent galvanometer, but the length of the needle has no falsifying influence on the result, because, when the reading is taken, the needle again lies in the plane of the ring. Therefore the sine galvanometer, invented by Pouillet in 1837—before the solenoid galvanometer was known—was preferred for the more accurate measuring of weaker currents. We have made use of the graduated galvanometer in order to perform our experiments quickly, and not to be delayed by calculations. The indications on this instrument of the current intensity are directly proportional ($J = k \times A$ where A signifies the number of degrees on the graduation scale). Of course the accuracy of the measurements depends on the trustworthiness of the graduation scale.

Page 317. 37. Schilling's priority of claim with regard to the invention of the magneto-electric telegraph, was recognised by Munke (in Gehler's *Wörterbuch*, 1838, ix.). Recently also by Zetzsche (*Geschichte der Telegraphie*, Berlin, 1877, p. 66), Netoliczka (*Illustrierte Geschichte der Elektrizität*, Wien, 1886, pp. 174–176). Curiously enough, German textbooks have taken no notice of this.

Page 342. 38. The proof of the induction current caused by moving a conductor in a magnetic field (fig. 146) was described by E. Grimsehl (*Programm der Cuxhaven Realschule*, 1893), and later by Szymański (*Postes Zeitschr.*, vii. (1903, I.), p. 10).

Fig. 145, together with the easier way of arranging the experiment, has been borrowed from Szymański; but, as comparative experiments proved, Grimsehl's experiment is preferable, although it demands special subsidiary apparatus.

39. *Alternating currents* show properties which distinguish Page 363. them from the ordinary or intermittent direct currents. They cannot be measured either by the galvanometer or by the voltameter of the usual construction, for the current impacts following in quick succession and opposite direction are without action on these, and particular apparatus are necessary to measure them, which we cannot go into. Also with them self-induction in a conductor, especially if it is wound in coils, is so considerable, that the resistance of a wire coil may be greater than that of a short air-space in a straight conductor. The resistance of a conductor for alternating currents is therefore essentially influenced by its shape (this is not so in the case of direct currents). Hence Ohm's law does not hold good for alternating currents. In direct currents the *efficiency* of equal wires of the same material is proportional to the surface of the cross-section. But this is not the case in alternating currents of higher frequency: it appears rather as if they did not flow through the interior of the wire, but, figuratively speaking, along its surface. Alternating currents of magneto-electric machines, or indeed those of dynamos constructed for an alternating current, are conspicuous for their intense physiological action, and if passed through the body may cause death. The experiments of Tesla, according to which currents of very high frequency (to 300,000 per second) and great electromotive force (60,000 volts and more) may be passed through the human body without any inconvenience being felt, seem to negative this. In 1893 these experiments were carried out and confirmed by Professor Iegorow at the Military Academy, before a large audience. As you know, waves of light of different length stream forth from a glowing body. Our eye only perceives those which make 400 to 800 billion undulations per second. We can, therefore, imagine that our *nerves* are only tuned to contain comparatively slow oscillations,

and hence cannot be excited by the stupendous velocity of Tesla's currents.

Page 383. 40. *Wave length of the ether waves* (fig. 156).

LIMIT OF PARTICULAR REGIONS, BY PROFESSOR DR P. LEBEDEFF OF MOSCOW.

A. *Forced electric oscillations*—	
Weber's earth inductor	$\lambda > 300,000$ km.
Pixii's magneto-electric machine (1837)	$\lambda = 15,000$,,
Alternating dynamo (50 periods per sec.)	$\lambda = 6,000$,,
,, ,, (102,000 periods per sec., Duddell (1905))	$\lambda = 3$,,
B. *Spontaneous electric oscillations in metal wires*—	
1. *Feddersen's oscillations*—	
Lodge (1888)	$\lambda = 600$ km.
Feddersen (1861)	$\begin{cases}\lambda = 24 \text{ ,,} \\ \lambda = 0{\cdot}6 \text{ ,,}\end{cases}$
Décombre (1898)	$\lambda = 0{\cdot}06$,,
2. *Spark telegraphy*—	
Marconi (1901)	$\lambda = 400$ m.
Demonstration apparatus	$\lambda \gtrless 3$,,
3. *Hertzian waves in wires*—	
Trowbridge and Danne (1895)	$\lambda = 114$ m.
Hertz (1887)	$\lambda = 9$,,
Marx (1898)	$\lambda = 0{\cdot}04$,
4. *Hertz' rays*—	
Hertz (1889)	$\lambda = 600$ mm.
Lebedeff (1895)	$\lambda = 3$,,
C. *Molecular oscillations*—	
1. *Visible spectrum*—	
Red light	$\lambda = 0{\cdot}76\ \mu$.
Violet light	$\lambda = 0{\cdot}38\ \mu$.
2. *Photographic waves*—	
Abney (1887)	$\lambda = 1{\cdot}3\ \mu$
Schumann (1892)	$\lambda = 0{\cdot}1\ \mu$.
3. *Heat waves*—	
Rubens (1898)	$\lambda = 61\ \mu$.
Pflüger (1902)	$\lambda = 0{\cdot}1\ \mu$.
Unknown interval	$\lambda = 3$ mm. $- 61\ \mu$.
Beginning of the unexplored region	$\lambda = 0{\cdot}1\ \mu\ (100\ \mu\mu)$.
Diameter of molecules of bodies	$\lambda = 1\ \mu\mu$.
,, negative electrons	$\lambda = 10^{-13}$ cm. $= 10^{-6}\ \mu\mu$.

(hence twenty octaves above the molecules of bodies).

APPENDIX

41. *New Rays, Radium Rays, Emanation.*—When Crookes, Page 384.
more than thirty years ago, was pursuing his researches with regard to the electric discharge in Geissler's tubes (p. 351), by exhausting the tubes more and more, he remarked that the "dark space" surrounding the cathode stretched continually further, and at last—when the tubes were almost empty of air—filled the whole tube. At the same time a new phenomenon appeared: rays streamed out of the cathode, perpendicular to the diameter of the tube, which caused the walls opposite to burst out in a bright fluorescence, and enabled him to cast the shadow of small metal plates on the opposite wall of the fluorescing glass tube, and to put in rotation little wheels of mica.

For twenty years these phenomena were known, but it was not until 1895 that Röntgen accidentally made the discovery that the glass wall struck by these cathode rays, or, better, a plate of heavy metal (platinum, iridium, or uranium), placed in the path of the cathode rays, generate the "anti-cathode," a new kind of rays.

These Röntgen or X rays are able to pierce the glass walls and to put certain bodies, like platino-cyanide of barium, in a state of fluorescence (see p. 352).

Crookes ascribed the phenomena observed by him to a fourth state of aggregation occasioned by the high vacuum, which he called the ultra-gaseous or radiant state of matter. The rays, he said, were caused by the emission of the smallest electrically charged particles, the so-called corpuscles and electrons (see p. 55), which acquire an enormous velocity in the electric field. The fact that a magnet can cause the deflection of these cathode rays substantiates this view, as ether waves cannot be deflected.

Crookes' theory remained unnoticed until recently, for discoveries have now been made which in the main confirm it.

After the discovery of the X-rays, Poincaré supposed that the fluorescing bodies had in themselves the power of emitting these rays. To prove this, Henri Becquerel in 1896 performed experiments and found that certain bodies, which he called "radio-active"—as especially pitchblende—send forth continuously a new kind of rays in some sort analogous

to the continuous electric molecular current of the magnets (see p. 231).

Madame Curie succeeded, after a very tedious series of experiments, in isolating the radio-active components of pitchblende and in liberating, in combination with chlorine or bromine, the new elements known as polonium, actinium, and the still more active radium. These metals have not yet been observed in an uncombined state. As yet only radium—as a chloride or bromide—has been obtained in sufficient quantities for examination, and the price is very high. For example, 1 mg. of radium bromide costs nearly £3; therefore 1 kg. of salt of radium (if it could be got) would come to nearly three million pounds.

Radium rays show in some respects the same qualities as the X-rays, that is to say, they cause screens covered with platino-cyanide of barium or zinc sulphide to fluoresce (as is elegantly shown in Crookes' spinthariscope); they act upon photographic plates and they ionize the air (see p. 353). These are so far the only means of detecting the radio-activity of bodies.

Later experiments have shown that there are three different kinds of radium rays, known as the α- β- and γ-rays.

The α-rays have a very weak penetrative force, *i.e.* they are entirely absorbed by a sheet of paper or layer of air a few centimetres thick; they are also very slightly deflected in a magnetic field, and in the opposite direction to the cathode rays. Probably the α-rays are formed of positively charged corpuscles, since the cathode rays consist of negative ones.

The β-rays have a very great penetrative force, are easily deflected in the magnetic field and in the same direction as the cathode rays. They act very strongly also on photographic plates.

The γ-rays have the greatest penetrative force of the three, and are not at all deflected by the magnet.[1]

[1] The peculiarities of these three classes of rays have been, since this was written, exhaustively studied by Professor Rutherford (see his *Radio-activity*, 2nd ed., or his *Radio-active Transformations*). The

Since the ether waves are not deflected by the magnet, we must accept the hypothesis that in this case (in the cathode as well as the α- and β-rays) we have to do with a radiation of the *smallest material particles* (corpuscles or electrons), and we may therefore distinguish two kinds of radiations: (1) radiations caused by the oscillations in the ether; (2) radiations caused by the emission of material corpuscles.

Thus Newton's emission theory has again come to the front. On the nature of the X-rays (and the γ-rays of radium) the opinion of men of science is still divided,[1] though most of them hold by the emission theory.

"It is curious that the first wave form of radiation known was initially considered to be due to an emission of corpuscles, and that the first type of the latter class of radiation was conversely mistaken for a peculiar kind of wave radiation" (Soddy, *op. cit.*, pp. 13–14).

It was also very surprising to discover that radium compounds give rise to a radio-active gaseous substance called the "Emanation," which has the power of imparting a temporary radio-activity to other bodies, and so saturating them that they show a greater intensity of radiation than the emanation itself. To this it may be possible that the radio-activity of the crust of the earth and that of old springs is to be attributed.

Since all five radio-active elements (uranium, thorium, polonium, actinium, and radium) possess a very high atomic weight, we can imagine that their atomic bodies are very great

velocity of the particles of which the β-rays consist, in some cases approach that of 2 or 300,000 kilometres a second; that of the particles of the α-rays about $\frac{1}{10}$ of this. The γ-rays are to all appearance equivalent to the Röntgen or X rays. Yet it seems to be proved that the α-rays are not all of the same velocity, and are deflectable in a magnetic field in differing degrees.—*Ed.*

[1] Professor Soddy says in his recent work (*Radio-activity*, London, 1904), p. 8:—"The X-rays like light are ether waves, and the difference seems to be that in the lower the disturbances are of the nature of sudden pulses very rapidly dying away, whereas in light there is a regular recession of undulations of the same kind. This, together with these probably extremely short wave-lengths, would account for the fact that the X-rays have not been reflected or refracted or polarized, although in their nature they so closely resemble light rays" (*cf.* p. 384).

in comparison with the other elements, that is, that they consist of a very great number of primary atoms. By the splitting up of these mighty atoms into less compact atomic bodies, on the one hand, single corpuscles (electrons) must be flung off like a bomb, with enormous velocity, and, on the other hand, new bodies formed.

In 1903 Sir William Ramsay discovered that the emanation of radium was changed, after a certain time, into helium, and this was afterwards confirmed by Prof. Soddy and Madame Curie.

We started with the discovery of the cathode rays by Crookes, and may close with the words of this long unappreciated genius, pronounced by him thirty years ago:—

"Here we appear at last to have beneath our hands and within the reach of examination the small indivisible particles which we may suppose to form the physical foundation of the world. We have actually touched upon the boundary line where matter and force seem to envelop each other, the realm of shades between the known and the unknown. Here, it seems, are laid the final realities."

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